This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

LIBRARY OF THE
UNIVERSITY OF MICHIGAN

DEPARTMENT
OF
ENGINEERING

THE GIFT OF
Publishers

TK
145
.S63

ELECTRICAL ENGINEERING

PRINTED BY
SPOTTISWOODE AND CO., NEW-STREET SQUARE
LONDON

ELECTRICAL ENGINEERING

FOR ELECTRIC LIGHT ARTIZANS AND STUDENTS

34344

(EMBRACING THOSE BRANCHES PRESCRIBED IN THE SYLLABUS
ISSUED BY THE CITY AND GUILDS TECHNICAL INSTITUTE)

BY

Sir W. William SLINGO

PRINCIPAL OF THE TELEGRAPHISTS' SCHOOL OF SCIENCE
DIRECTOR OF THE ELECTRICAL ENGINEERING SECTION, PEOPLE'S PALACE, LONDON

AND

A. BROOKER

INSTRUCTOR IN ELECTRICAL ENGINEERING AT THE TELEGRAPHISTS' SCHOOL OF
SCIENCE AND AT THE PEOPLE'S PALACE, LONDON

With 307 Illustrations

LONDON
LONGMANS, GREEN, AND CO.
AND NEW YORK: 15 EAST 16th STREET
1890

All rights reserved

PREFACE

We have frequently been asked by artizans and students to recommend a single work covering the whole field of Electric Lighting. Our inability to comply with this request has prompted us to endeavour to fill such a palpable gap in the literature of technical science. We have designed this book to cover the extensive syllabus of the City and Guilds of London Institute, and have so enlarged its scope as to make it embrace the requirements not only of those actually employed in the electric lighting industry, but also of those who, while having little or no electrical knowledge, have under their supervision various kinds of electrical machinery. The work should therefore prove of service to such men as marine, railway, and tramway engineers, naval officers, municipal officials, and managers of mines and factories.

We recognise to the full the fact that, as a rule, the most successful electrical engineers are evolved from good mechanical engineers, and have striven to give our readers, even though they may possess no previous electrical knowledge, a clear insight into the purely scientific as well as the practical part of the subject. Every effort has, however, been made to embrace only the essential branches of the pure science, omitting those which, while interesting and serviceable in other fields, are not required in electric lighting or the electrical transmission of power. It is hoped also that we have succeeded in the difficult task of explaining the subject clearly and in simple language. The close connection between the three kinds of electrical phenomena, static or frictional, dynamic or current, and magnetic, has been carefully explained and made to follow naturally. It is believed that the fact that magnetism is primarily but a consequence of dynamic electricity, or the more or less permanent effect on certain substances of an electrical disturbance, instead of being a separate and distinct series of phenomena, has not hitherto been so plainly and unhesitatingly expressed. It is our firm conviction that in the near future, this view of the question is the one which will be universally adopted. The conception of 'lines of force' is one of great value to the student, and he will find them here reasoned about as having a tangible existence. It would be impossible to describe every piece of apparatus or machinery in actual use, and we have selected those which, while having proved in practice to be among the best in their respective classes, also serve to illustrate in the readiest manner the laws and principles involved. In a few cases, however, the apparatus can scarcely be said to have been successfully applied, but they have been introduced as indicating the highest present developments in directions in which success will probably be attained.

Although primary batteries are not used to any great extent in electric lighting, except for testing and other similar operations, yet a considerable amount of space has been devoted to them, and to the experiments which can readily be performed by their aid, because long experience has taught us that they afford in the readiest way a clear insight into the fundamental principles of the science and the various laws so far discovered.

An unusually large number of the explanations have been based upon Ohm's law and its consequences. Mathematical formulæ and explanations have, where possible, been avoided; where they do occur they are invariably simple, and are generally accompanied by arithmetical examples. As they merely supplement the ordinary explanations, they can usually be ignored without the meaning being missed; but those able to solve a simple equation will find very little indeed which cannot easily be followed.

W. S.
A. B.

CONTENTS

CHAPTER PAGE

I. CURRENT—POTENTIAL—CONDUCTORS—INSULATORS . 1

II. PRACTICAL UNITS—OHM'S LAW—FUNDAMENTAL UNITS . . 12

III. PRIMARY BATTERIES 43

IV. MEASUREMENT OF CURRENT STRENGTH 82

V. MEASUREMENT OF RESISTANCE 131

VI. MEASUREMENT OF ELECTRO-MOTIVE FORCE 163

VII. ELECTRO-MAGNETS—ELECTRO-MAGNETIC INDUCTION . . 202

VIII. DYNAMO-ELECTRIC MACHINES (ALTERNATE CURRENT) . . 230

IX. DYNAMO-ELECTRIC MACHINES (DIRECT CURRENT) . . 270

X. DIRECT CURRENT DYNAMOS—*continued* 317

XI. DIRECT CURRENT DYNAMOS (OPEN COIL) 380

XII. MOTORS AND THEIR APPLICATIONS 402

XIII. TRANSFORMERS 444

XIV. SECONDARY BATTERIES 466

XV. ARC LAMPS 492

XVI. INCANDESCENT LAMPS—PHOTOMETRY 526

XVII. INSTALLATION EQUIPMENT, FITTINGS, ETC. 575

INDEX 623

ELECTRICAL ENGINEERING

CHAPTER I.

CURRENT—POTENTIAL—CONDUCTORS—INSULATORS.

When a stick of sealing-wax is rubbed with a piece of dry fur or flannel, the wax acquires the power of attracting to itself any light substances that may be in its vicinity. By taking suitable precautions a like power can be detected in the fur or flannel. Similar phenomena can also be produced by the rubbing together of other substances, such as glass and silk, india-rubber and silk, brown paper and a bristle clothes-brush, &c. A body which exhibits this power of attraction is said to be endowed or charged with electricity, or to be electrified.

But there are two electrical states, and this can be easily proved, for if by means of a foot or so of silk ribbon we suspend the electrified sealing-wax and bring near it another electrified stick of sealing-wax, repulsion ensues, that is to say, the suspended rod recedes from the approaching one. On the other hand, if certain necessary precautions have been taken to prevent the neutralisation or escape of the electricity that was generated on the fur or flannel rubber, it will be seen, on bringing it near the suspended sealing-wax, that attraction takes place. A similar result would follow if a warm glass rod were rubbed with a piece of dry silk and then brought near the sealing-wax. On suspending, however, the electrified glass and bringing the electrified fur near it, repulsion would take place. It is manifest, then, that as electrified glass attracts electrified sealing-wax, but is repelled by or repels electrified fur, there are two electrical states, one on the sealing-wax, which is called negative, and the other on the fur, which is called positive. It is also clear that bodies similarly electrified are mutually repellent, while bodies dissimilarly electrified are mutually attractive. This matter will again be referred to, but the point to which especial attention is now directed is that the amount of electricity developed by rubbing the two bodies—say the sealing-wax and the fur—together bears no direct relation to the amount of actual friction to which the bodies are subjected, for what is really essential in order to obtain the highest possible degree of electrification is to bring every portion of the one surface into intimate contact with every superficial particle of the other, and when that is done, no extra amount of rubbing can develop any further degree of electrification.

Speaking generally, then, it may be said that when any two bodies are rubbed together electricity is produced, although it frequently happens that the amount is so small as to render its detection very difficult. If, however, delicate apparatus, which we will not pause here to describe, is employed, very feeble charges can be indicated. In fact, if a piece of zinc and a piece of copper are simply placed in contact the feeble charge of electricity then developed can easily be rendered evident. If the same pieces of metal are placed in saline or acidulated water, a similar result follows, although in this case the water itself becomes an important factor in determining the resultant electrification. The end of the zinc outside the liquid will be found to possess properties similar to those of the sealing-wax after it has been rubbed with fur. It is, therefore, said to be negatively electrified. The copper, on the other hand, will have an electrical state similar to that of the fur itself, or of the glass which has been rubbed with silk, and it is therefore said to be positively electrified.

It follows that whether the electricity is the result of so-called friction or whether it is a consequence of the simple contact of two dissimilar bodies, it is with precisely the same *kind* of force that we have to deal, and the old distinction between 'frictional' and 'galvanic' electricity, which used to be urged with considerable persistence, is virtually a myth. The quantity of electricity may vary, and we may view it in its two phases, positive and negative, but neither of these considerations can affect the character of the force.

It may be accepted as a general fact that when the same kind of force is bestowed upon two points or bodies, but to a different extent in the one case as compared with the other, there is a universal tendency to equalise the distribution of the force—that is to say, to produce equilibrium, and this equilibrium will be established when the conditions become such as to render it possible. Reverting again to the zinc and copper plates partly immersed in water, the exposed ends will be electrified to different degrees. There will be a tendency to produce equilibrium, or, as it is more generally called, neutralisation. This will be accomplished if the necessary facilities are afforded, and until this is done the intervening space will be subjected to what may be called an electrical stress. It is found by experiment that a piece of metal affords the readiest means of relieving the strain due to this stress, thus facilitating neutralisation, for on joining the two plates together, say by a piece of copper wire, a momentary rush of electricity from the one to the other will take place. This phenomenon is that which is generally known as discharge, and it affects the whole combination, including the liquid and the metal surfaces in contact with it.

This brief spasmodic flow or rush of electricity, whose function it is to restore the electrical equilibrium, causes, however, a series of chemical changes to take place in the liquid itself, among other things a portion of the zinc being dissolved and converted into what is called a salt of that metal. These chemical reactions cause in their turn a fresh electrical difference between the plates, which is followed immediately by another equilibriating flow, and that by a further difference, and so on. These changes follow one another in exceedingly rapid succession, so rapid, in fact, that it is a matter of absolute impossibility to distinguish them separately, and we have consequently what appears to us as, and what is known as, a continuous 'current' of electricity.

A little reflection will make it evident that by following out the line of experiment and deductions here indicated, the so-called single and double fluid theories of electricity are both disregarded, not simply for the sake of disregarding them, but because they are unnecessary and involve considerations and concessions which are not warranted by the circumstances. In point of fact, electricity is not a fluid at all, and only in a few of its attributes is it at all comparable to a fluid.

Let us rather consider electricity to be a condition into which material substances are thrown, and that *all* such substances partake more or less of this condition, just as we say that all bodies are heated, although to varying degrees, and that in virtue of this heat their particles are set into more or less rapid vibration.

Moreover, as in the case of a heated body, there is a region surrounding an electrified body in which the force due to the tendency to produce electrical equilibrium can be made evident. This is shown by the fact already referred to that two bodies in a similar electrical state repel one another, while others in different electrical states attract. It is inconceivable that such an effect as the imparting of motion to a mass of matter could be produced without the aid of some medium capable of transmitting the force. What this medium actually is is a matter of doubt, and we cannot experimentally determine the question. So also is the mode or method of transmission. Under such circumstances it becomes convenient to picture to ourselves the propagation by means of *lines of force*, travelling through an infinitely elastic, imponderable medium, or substance, as it is sometimes called, which is assumed to pervade all matter and all space, and which is known as 'ether.' Granted that these lines of force may have no actual existence, the conception is, nevertheless, exceedingly useful, and facilitates an accurate estimation of the way in which electrical phenomena are set up, so much so, that the idea imperceptibly grows upon the student, and to him the lines of force become endowed with a definite meaning.

There are three features about these lines of force to which we may now draw attention. In the first place, their assumed position indicates the path along which the action takes place; secondly, their direction indicates the direction in which the force is transmitted; and, thirdly, their density, or the number occupying a given space, measures the strength or magnitude of the force. Having given to these lines of force position, direction, and density, we can predict the result which should follow in any given electrical field. For the action is always as if the lines of force endeavour to coincide in direction, and then to shorten themselves, the magnitude of the action being simply dependent upon the density of the lines.

In the case of an electrified sphere suspended somewhere in space and remote from every disturbing element, the lines of force would be radial and equidistant in position, their density would depend upon the degree of the electrification or the quantity of the charge, while their direction, that is, radially inwards or radially outwards, would depend upon whether the charge were negative or positive.

Let us assume a positively charged sphere to be suspended, with its lines of force directed outwards, and a second sphere, negatively charged, with its inwardly directed lines of force, to be brought into the vicinity of the first sphere ; it will be evident that many of the lines of force of the two spheres will bend or turn round and concentrate themselves within the space intervening between the spheres. The lines of force will now be similar in direction, and, owing to the shortening tendency above referred to, attraction results.

The attraction, presuming it to be sufficiently strong, will impart motion to one or both of the spheres, or, in other words, work will be performed. Now this capacity for doing work arises solely from the electrification, and the quantity of work performed is proportional to the degree of electrification. But 'capacity for doing work' and 'potential' are convertible terms—that is to say, anything which possesses the capacity for doing work is said to have a certain potential, consequently the degree of electrification of any body is known as its potential. We have previously said that the tendency to produce, between two electrified points or bodies, a state of electrical equilibrium, is proportional to the difference of their degrees of electrification. In technical language this means proportional to their difference of electrical potentials. Therefore, in the case of the zinc and copper plates immersed in acidulated water, the flow of electricity from the exposed end of the copper to the exposed end of the zinc is correctly described as being due to a difference of potential between those ends.

If the student has grasped what has already been said, he will be able to readily apply the doctrine of potential to special cases; for example, it will be evident that no two parts of the same body (providing it is one that can transmit or propagate the flow of electricity) can remain for any length of time at different potentials, for the moment a difference of potential is established an electrical stress is set up, and the flow of electricity follows as a necessary or natural consequence. On the other hand, where there is no difference of potential there can be no flow of electricity. So that we come to these conclusions--viz. that electricity always flows between two bodies which are at different potentials; that it flows from the body possessing the higher to that possessing the lower potential; that in the case of the 'current' maintained by the 'simple cell,' composed of zinc and copper plates dipping into acidulated water and described in a previous page, we had a difference of potential established on the zinc and copper extremities; that on joining these extremities together there was a flow of electricity to produce equilibrium; that this, by means of the chemical changes, re-established a potential difference; and that these actions and reactions, being alternated with infinite rapidity, appear to us as a continuous current.

We may, therefore, define a 'current' as the expression of an effort ever being made to establish electrical equilibrium between two points which are ever being electrified to different potentials. Neither of these objects is attained—that is to say, a difference of potential is never permanently established on the one hand, and, on the other, equilibrium it is impossible to maintain.

Let us further consider the case of the simple cell, the zinc and copper of which, however, instead of being joined together, are each connected to long pieces of wire, whose other or free extremities are inserted in the earth at different places. It used to be the general assumption that in this case the current would flow from the copper plate to the earth, and through the earth to the other wire, up which it would pass and so return by the zinc to the battery. But anything more unreasonable than such an hypothesis it is really impossible to conceive. To demonstrate this we need only take into consideration the state of affairs at the Central Telegraph Office in London, where there are 1,000 different circuits or lines, one end of each battery being joined to the same earth plate under the office, the other ends being joined to the respective lines, which in their turn are joined to earth plates at the distant ends. Viewed in its real aspect, this 'earth-return' theory compels the assumption that the 1,000 currents which go to earth at as many different places—some at Newcastle, some at Liverpool, others at Cardiff, Yarmouth, &c., others, again, only a few hundred yards away in several of the City thoroughfares—all return through the earth to the earth plate or connection under the Central Office, where each individual current has to pass the other 999 currents travelling through the plate, and single out the particular wire joined to the particular battery from the other end of which it emanated, and is not satisfied or has not completed its work until it thus gets safely home again. It will readily be seen that, if such were actually the state of affairs, the laws above stated, that electricity only flows under a difference of potential and always flows when there is that difference, would be nullified.

Like everything else in the universe, the earth itself is always more or less electrified, and, as a consequence, it is always at a certain potential. It will therefore be seen that, were a body which had been electrified to a higher potential than the earth to be connected with the earth, a flow of electricity would take place passing from that body to the earth, so that both the body and earth assume the same potential, and it may be mentioned that the passage of this flow could be easily observed by the introduction of certain apparatus. On the other hand, were a body to be electrified to a potential lower than that of the earth and to be connected with it, a flow of electricity would be determined between the earth and the body, and the passage of this electricity could also be rendered evident. Consequently, when copper and zinc strips are immersed in acidulated water and the exposed ends become electrified, the one to a higher and the other to a lower potential than the earth, the connection of those extremities with the earth causes a flow of electricity from the plate of higher potential to the earth, and from the earth to the plate of lower potential. These flows will be equivalent to joining the plates directly together and so releasing the electrical stress.

Thus is it with every battery: the potential of the earth is above that of one end of the battery and below that of the other end. There is then no need for a current to flow between the two earth-connections, and the assumption of such a state of affairs is quite gratuitous. It must not, however, be supposed that the flow of electricity from or to the earth can sensibly affect its charge or potential, the terrestrial charge as a whole being so enormous as to make any other charge or potential incomparably feeble and insignificant. To make this clearer we will employ an analogy. Let us suppose that we have two tanks containing water, the bottom of one being placed ten feet above the level of the ocean, and the other, which we will suppose to be very deep, immersed until the surface of the contained water is ten feet below the ocean level. If now we suppose holes to be made in the bottoms of the tanks, all the water will flow out of the higher tank into the sea below, while water will flow up into the lower one until the ocean level is reached. But of course no one would contend that these changes would make any difference in the level of the surrounding waters, even if more water were received from the higher tank than was given to the lower, and what is true in this case is equally true in the case of electricity. In fact, the earth is a body whose capacity for electricity, so far as we are concerned, is infinite, and nothing that we can do can alter its charge. The man who would assert that when he joins one end of his battery to earth, say, at London, and the other end to earth, say, at Aberdeen, and that in consequence a current flows through the earth from one connection to the other, asserts, in fact, although he may not know the significance of his contention, that he places these two points in London and Aberdeen at different electrical potentials. He might as reasonably contend that if he turns on his water-tap into the Thames at London and digs a hole in the bank of the river at Windsor, he sets up a difference of level between the two places, and causes the water which he pours in at London to travel up against the stream and fall out at Windsor.

We come now to a real difficulty—a solution of which is improbable, although it is, perhaps, in the future not impossible—and that is, to be able to say with certainty in which direction a current really travels, or, in other words, to declare which of two differently electrified bodies has the higher, and which the lower potential. All we can say with any certainty is that there is a difference of potential, and that therefore the current flows from the point of higher to that of lower potential. It is usual to assume, in the present incomplete and imperfect state of our knowledge concerning the nature and propagation of electricity, that the electric state which we know as positive has a higher potential than that state which we know as negative, whence we say, or assume, that electricity flows *from* a positively electrified *to* a negatively electrified body. And we will in this work follow this assumption, true or otherwise, as it involves no sacrifice of principles, notwithstanding the fact that experiments have been performed which tend to show that that state which we call negative is really of higher potential than that which we call positive.

Reference has several times been made to the use of wire as a means of connection between two oppositely electrified bodies, or between two bodies at different potentials. Were we desirous of transmitting mechanical instead of electrical energy, a hempen or silken cord would answer equally well, if due provision had been made that the cord should have the requisite mechanical strength or tenacity to transmit the energy without fracture. But tenacity is not the necessary attribute for a body to possess in order that electricity may be readily propagated through it. All substances admit of this transmission, although to very varying degrees. A piece of copper wire offers greater facilities than a piece of iron wire of similar dimensions, which in turn offers greater facilities than a similar piece of German-silver wire. But the metals one and all are enormously superior in this respect to the great bulk of non-metallic substances. On the other hand, every substance, whatever its nature, offers a greater or less amount of resistance to the transmission of electricity. Bodies which offer little resistance to the electric flow are said to be good conductors, while those which offer considerable resistance are said to be bad conductors or insulators. To the former class belong the metals, carbon, ordinary water, &c., the latter class including such substances as glass, air, sulphur, resin, india-rubber, and ebonite. Between these two classes are many substances which might be included in either class, but no hard and fast line can be drawn.

It has been shown that the result of joining directly together two bodies electrified to different potentials is a flow of electricity from the body charged to the higher potential, to that charged to the lower until electrical equilibrium between the two bodies is obtained. And a similar result follows if we join the bodies together by a piece of wire; while if they have only air or some other bad-conducting substance separating them, there will be no flow at all, or only a very feeble one. If the path of the flow is made longer, or more difficult, say by the interposition of a longer or poorer conductor, it naturally follows that the time which is taken for equilibrium to be restored is lengthened, and the rate of restoration, that is, the strength of the current, is less. But if the potential difference and the quantity of electricity transferred is the same in the two cases, the energy expended in the effort to restore equilibrium is the same.

The result, then, of interposing a substance of poorer conducting power, or, what amounts to the same thing, of higher resistance, between two bodies having a potential difference, is to reduce the strength of the flow or current passing from the one to the other. We can find a very simple analogy to this if we suppose two tanks of water at different heights one directly above the other. So long as the bottom of the higher one is intact the resistance to the flow of water from it to the other is practically infinite, but if we interpose a relatively bad conductor of the water in the form of a very small pipe or tube between the water in the tanks, there will be a correspondingly weak or feeble flow of water from the higher to the lower tank. If we increase the size or bore of the pipe, the conducting power will be increased proportionally, and a corresponding increase in the volume of the water (or in the strength of the current) flowing will be observed. Pursuing this to its finality, if the bottom of the upper tank is removed instantaneously there will result an equally instantaneous fall of the whole of the water in the tank. Such a state of things can easily be traced between two bodies charged to different electrical potentials and connected by various substances whose conducting powers range from the almost infinitely great to the almost infinitely small, or, in other words, by varying the amount of resistance which is here shown to be the inverse or reciprocal of conductivity, we can, in a corresponding value, vary the strength of the current.

To summarise our observations on the question of resistance, we may say that if we electrify two bodies, connected only by the air, to different potentials, we subject the intervening air to a species of stress. If we very considerably increase the potential, the air being no longer able to sustain the stress, a discharge or an electric flow ensues. A similar result can be achieved without increasing the potential difference, by reducing the distance between the electrified bodies, or by bridging over the air-space with a piece of wire or other good conductor. In either case the ability to sustain the stress is reduced, and we call this ability to sustain the stress resistance. The more resistance we insert between the electrified points or bodies, the more do we thereby reduce or prevent the flow of electricity.

CHAPTER II.

PRACTICAL UNITS—OHM'S LAW—C.G.S. SYSTEM.

IN dealing, in the previous chapter, with the general attributes of electricity, the only degree of comparison arrived at was to say that one electrification, resistance, or current was greater or less than another. And to a somewhat considerable extent this was, until within the last few years, deemed sufficient. It is, however, now essential that more precision in comparing or measuring forces and their properties and effects should be obtained. Measurement is, in fact, the most important branch of electrical science, as, indeed, it is of every other physical science.

Instead of simply saying that one lump of iron is heavier or weightier than another, it is usual to say by how much they differ. Thus one lump may have a mass of ten pounds, and another a mass of twenty pounds. The latter is therefore ten pounds heavier than the former. We have here introduced a unit of measurement, viz. the pound, or unit of mass. Similarly, the inch or foot may be used as a unit of length, the second as a unit of time, the pint as a unit of capacity, the sovereign as a unit of coinage, and so on. These units are all such as everybody can readily appreciate. They are so frequently employed that no mental effort is required to understand what is meant when any one of them is mentioned.

In dealing with electricity the first thing we wish to measure is naturally the amount of the electrical difference between two bodies which causes an electrical stress and which may result in a current of electricity. But we are confronted with two difficulties. The first is that by none of the everyday units—by no unit employed for any other purpose—are we able to indicate exactly the electric potential in a body. Moreover, electricity being but a condition of matter, and not matter itself, it is impossible to measure it directly. We can only measure it by its effect upon material substances. In the next place, inasmuch as it is impossible to obtain or even to conceive of a body altogether devoid of electrification (although it is not always perceptible), it is impossible to fix on an absolute zero potential, and measure potentials from that point; in just the same way that it is impossible to have a zero level, some arbitrary point such as the sea-level at high tide having to be employed if we wish to measure the relative height of two or more points. It is, consequently, necessary to look elsewhere for a starting-point, and to fix on a convenient arbitrary potential zero. We take as a zero the potential of the earth's surface, and bodies which are said to be positively electrified are at a higher potential than the earth, while negatively electrified bodies are at a lower potential. Positive and negative potentials may therefore be said to correspond to height and depth in their relation to the sea-level. Inasmuch, however, as we are unable to detect any potential at all unless we take two points or bodies whose potentials are different, the measurement of potential itself again presents difficulties. On the other hand, when we are called upon to measure the potentials of two bodies, what we really desire to know is the difference between those potentials; or, if we call the potential of one body P, and that of the other P_1, we want to know the value of $P-P_1$; for, after all, it is this difference of potential that determines the flow of electricity. This difference of potential is known as electro-motive force, which is frequently contracted into the initials E.M.F., or, shorter still, into E. only. It is this electro-motive force, then, that we desire to measure, and the practical unit by which it is measured is known as the 'volt.' We will, for the present, rest satisfied with the simple statement that the volt is approximately equal to, although actually a fraction less than, the electro-motive force of a single Daniell cell. (See Chapter III.)

Reference was made in the previous chapter to 'resistance,' and it was described as the converse of conductivity, which again we described as the ability of a body to transmit a current of electricity. It is easy to show that resistance may be expressed as a ratio—the ratio of electro-motive force to current—and many authorities insist that it should always be regarded thus. It may also be expressed as a 'velocity,' or the ratio of length to time, but we prefer to deal with it as it appeals to practical electricians—viz. as an attribute of matter, varying with different substances, and in virtue of which such matter opposes or resists the passage of electricity, whence the current has to do 'work' or expend 'energy' in effecting the passage. The law of the conservation of energy teaches us that force is indestructible, and it follows, therefore, that if energy has to be expended in impelling a flow of electricity against a greater or less amount of resistance, the equivalent of that energy must be developed in some other form. This other form is usually heat; or, in other words, when a body opposes a certain amount of resistance to the passage of electricity, heat is produced, the actual amount of heat being an exact counterpart of the energy expended in overcoming the resistance, and varying therefore directly as that resistance. Consequently, if we have two conductors, the resistance of one of which is twice that of the other, and if we send currents of equal strength through both wires, twice as much heat will be developed in the conductor of the higher resistance as will be developed in that offering the lower resistance. We shall have occasion to deal with this subject more fully in a future chapter, but we may add here, that if we wish to perform work at any point by means of an electric current conducted by a wire to that point, we must keep the resistance of that wire down to the lowest practical limit, because every fraction of the energy frittered away in heating the conductor means so much less energy available for the particular work which we wish the current to perform. It is apparent, then, that we require a unit by which we shall be able to compare the resistances of various substances, and the unit selected is called the 'ohm.' It was decided by an International Congress of Electricians which assembled in Paris in 1884 as being equal to the resistance which is offered to the flow of electricity by a column of mercury one square millimetre (0·03937 of an inch, or a small fraction less than $\frac{1}{20}$ of an inch) in section, and 106 centimetres long (the centimetre is equal to 0·3937 of an inch), the temperature being at the freezing point (32° Fahrenheit or 0° Centigrade), and the pressure of the air equal to the pressure at the base of a column of mercury 30 inches, or 760 millimetres, in height. The Congress which determined the value of this unit also decided that it should be known as the 'legal' ohm. A millionth part of this unit is called a microhm, and one million ohms a megohm.

There have, in the past, been an almost unlimited number of units, more or less crude and unreliable; for it must be borne in mind that for a unit to be of any real value it must be permanent or durable, it must be capable of confirmation, and its derivation must be well known and invariable. One of the earlier units of resistance was that offered by a mile of the then best procurable iron wire of a certain gauge or diameter. The indefiniteness of such a unit may be conceived when it is called to mind that even now no two samples of the same wire will offer the same resistance; and still more so was this true a few years ago, when the quality of iron wire as a conductor was vastly inferior compared with what it now is, both as regards its actual resistance and its uniformity.

The only other unit which we need consider is that known as the B.A., or British Association Unit. It was determined in London in 1863 by a committee appointed for the purpose by the British Association, and the method of determination then adopted was the basis upon which the Paris or legal ohm was afterwards calculated. These units are both based on what is called the C.G.S. system (p. 40), the Paris unit being really a correction of the B.A. unit. The practical standard of the former has, however, a great advantage over that of the latter, which consisted of the resistance of a certain length of wire carefully preserved in London. This was, of course, rarely used, and duplicates of the standard had to be employed for comparing or standardising other resistances. The legal ohm is manifestly capable of being reproduced more easily, and it is this fact which imparts to it its chief value. The B.A. unit is a fraction smaller than the Paris ohm, the actual proportion being 0·986 to 1·0. If it were possible at the present day to universally adopt a common unit, it would certainly be a great advantage, for then everybody would know what was meant when anybody else mentioned any particular resistance. But prior to 1884 a vast quantity of electrical apparatus and machinery was in use, and everything in England and some other countries was measured by the B.A. unit, while the measurements employed on the Continent were for the most part referrible to the Siemens unit, which was the resistance of a column of mercury 1 metre (or 39·37 inches) long, the other details as to its size, temperature, and pressure being the same as those employed in devising the legal ohm. As it was, the various administrations and authorities were placed in a most unpleasant dilemma. If they re-standardised and re-marked all their existing apparatus they would have had to incur enormous expense, while if they continued the use of their existing standards they would be perpetuating an inconvenience which they had called the Congress together to remove. In the majority of cases, questions of finance compelled them to adopt the latter alternative, so that with us, most telegraph apparatus continues to be measured by the B.A. unit, while the apparatus employed in the newer industries, such as electric lighting, is measured by the legal ohm. Accordingly, in this work we shall endeavour to keep the latter in view.

The student will frequently come across the expression 'specific resistance,' and it is a most important term. It may be defined as the resistance of any particular substance as compared with the resistance of a piece of some other conductor, such as silver, of similar dimensions, the test being made under similar conditions. It is a matter of great convenience that different bodies vary in their relative or specific resistances, for there are times when we want the lowest possible resistance, while at other times we require a large measure of resistance, more particularly when we desire to prevent an electric discharge, to prevent the flow of an electric current, or to prevent electricity leaking from one body to another. Appended is a table based upon that of Dr. Matthiessen which shows the relative resistance of a number of metals frequently met with, and as the variation of the temperature of a body varies its electrical resistance, all the tests have been taken at a common temperature, viz. that of freezing point, or the necessary corrections made to correspond to that temperature.

An alloy of copper, nickel, and zinc (the usual constituents of German silver), combined with 1 or 2 per cent. of tungsten, was introduced a few years ago under the name of platinoid. It is found that the addition of tungsten imparts greater density to alloys

TABLE SHOWING RELATIVE RESISTANCES OF CHEMICALLY PURE SUBSTANCES AT 0° C. IN LEGAL OR PARIS OHMS.

Name of Metal	Relative Resistance	Resistance of a wire 1 foot long, 1/1000 of an inch in diameter	Resistance of a wire 1 metre long, 1 millimetre in diameter	Resistance in microhms	
				Cubic inch	Cubic centimetre
Silver, annealed . .	1·000	9·048	0·01916	0·5921	1·504
Copper, annealed . .	1·063	9·612	0·02034	0·6292	1·598
Silver, hard drawn . .	1·086	9·830	0·02080	0·6433	1·634
Copper, hard drawn .	1·086	9·831	0·02081	0·6433	1·634
Gold, annealed . .	1·369	12·38	0·02620	0·8102	2·058
Gold, hard drawn . .	1·393	12·60	0·02668	0·8247	2·094
Aluminium, annealed .	1·935	17·53	0·03710	1·147	2·912
Zinc, pressed . . .	3·741	33·85	0·07163	2·215	5·626
Platinum, annealed .	6·022	54·49	0·1153	3·565	9·057
Iron, annealed . .	6·460	58·45	0·1237	3·825	9·716
Lead, pressed . .	13·05	—	0·2498	7·728	19·63
German silver, hard or annealed . . .	13·92	125·91	0·2666	8·240	20·93
Platinum, silver alloy (⅓ platinum ⅔ silver) hard or annealed . .	16·21	146·70	0·3106	9·603	24·39
Mercury . . .	62·73	572·30	1·211	37·15	94·32

and reduces any tendency to oxidation. When polished, the alloy is scarcely distinguishable in appearance from silver. A cubic centimetre offers a resistance ranging from about 30 to 36 microhms, so that its resistance is about one and a half times that of German silver. As, however, alloys always vary more or less in their composition, a definite resistance cannot safely be assigned to any commercial variety, and calculations concerning them can only be accepted as actually true of the particular samples tested. Platinoid, when drawn hard, is, like copper, softened by heating and sudden cooling.

The admixture of even a minute proportion of foreign matter very considerably reduces the conductivity or increases the resistance of a metal. A very remarkable effect is observed when an alloy of two or more metals is tested, for the specific or relative resistance of the alloy will always be found higher than that of either of its constituents. Purity in the case of simple substance, and absolute uniformity in the constitution of alloys, such as German silver, is, therefore, pre-eminently essential, if the highest conductivity or if a certain specific resistance is desired, as is shown by the following table, giving the specific conductivities of various samples of copper.

TABLE SHOWING THE COMPARATIVE CONDUCTIVITY OF PURE COPPER AND THE BAR COPPER OF COMMERCE.[1]

(*All the wires were annealed.*)

	Conducting power.
Pure copper	100·0 at 15·5° C.
Lake Superior, native, not fused	98·8 at 15·5° C.
Ditto, fused, as it comes in commerce	92·6 at 15·0° C.
Burra Burra	88·7 at 14·0° C.
Best selected	81·3 at 14·2° C.
Bright copper wire	72·2 at 15·7° C.
Tough copper	71·0 at 17·3° C.
Demidoff	59·3 at 12·7° C.
Rio Tinto	14·2 at 14·8° C.

Or, again, if the relative conductivity of pure copper is taken as 100, then that of copper mixed with 1·6 per cent. in volume of silver will be only 65; while the conductivity of silver mixed with 1·2 per cent. in volume of gold will be 59 when that of pure silver is taken as 100.

A highly interesting phenomenon is the wonderful effect which a variation in temperature produces upon the resistance of the various substances through which a current may flow. The effect would be less surprising were it general or were it consistently uniform in all bodies, but the great feature to be observed is that while in the case of metals the resistance of a conductor invariably increases with an exaltation in temperature, the non-metals all show a decrease in resistance under similar circumstances. It is also a remarkable feature that in the case of metals the variation is much less in alloys than in pure metals. These results are fraught with the greatest importance, as they limit considerably the number of substances available for many classes of electrical apparatus. For example, wires which are to be employed as standards for comparing or measuring resistances should have as nearly as possible the same value at all temperatures. It may be observed that the insulating coatings of the wires in the telegraph cables laid in such waters as the Indian Ocean show a marked decrease in their insulating properties after submergence, consequent upon the fact that the water is several degrees warmer than that in the tanks in which the standardising tests were made. The accompanying table, showing the percentage variation in the resistance of various bodies between the temperature of freezing water and that of boiling water, should prove eminently interesting. It is certainly useful and important.

---

[1] Report of the Government Submarine Cable Committee.

Name of Metal	Conducting power at 0° C. Silver = 100	Percentage fall of conducting power between 0° and 100° C.
Pure iron	16·81	39·2
Pure thallium	9·16	31·4
Other pure metals in a solid state	—	29·3
Gold with 15 p.c. iron	2·76	27·9
Proof gold	72·55	26·4
Standard silver	80·63	23·2
Gun metal (Austrian)	27·08	18·3
Copper with 25 p.c. platinum	22·08	11·5
Silver with 5 p.c. platinum	31·64	11·3
Silver with 9·8 p.c. platinum	18·04	7·1
Copper with 9·7 p.c. tin	12·19	6·6
Gold silver alloy	15·03	6·5
Platinum with 33·4 p.c. iridium	4·54	5·9
German silver	7·80	4·4
Gold with 4·7 p.c. iron	2·37	3·8
Silver with 25 p.c. palladium	8·52	3·4
Silver with 33·4 p.c. platinum	6·70	3·1
Platinoid	—	2·09

As may have been gathered from what has already been said, when we increase the length of a conductor we invariably increase its resistance. This follows as a matter of course from the fact that if we urge a certain current through a wire of increased length, we give it more work to do, necessitating, consequently, a greater expenditure of energy in precisely the same way that a railway engine would consume more coal in taking a train a distance of 200 miles than it would consume in taking it only half that distance. The resistance of a conductor of uniform material and thickness or cross-section varies directly as its length—that is to say, if we vary the length of the conductor we vary its resistance at exactly the same rate, or, in fewer words, resistance varies directly as the length of the conductor. If a mile of wire of a certain gauge offers a resistance of ten ohms, two miles of the same wire would offer twenty ohms.

The effect of increasing the size or sectional area of a conductor is to increase its conductivity and, consequently, to diminish its resistance, in exactly the same way that increasing the diameter of a pipe increases the amount of gas or water that can be passed through it. The resistance of a conductor varies inversely as its sectional area. That is, if we have two conductors, such as two specimens of copper wire, drawn from the same bar, the amount of resistance which the wires will offer depends upon the size of the wires or on the area of the ends exposed on cleanly cutting them at right angles to their length—that is to say, upon the amount of metal through which the current can flow. Most wires are round, so that the section is a circle; and it becomes necessary to understand the method of comparing the areas of circles. The area of a circle varies as the square of its diameter; for example, if we have two circles, one having a diameter of one-tenth of an inch and the other of two-tenths of an inch, their areas or the spaces they enclose will not be in the proportion 1 : 2, but as the squares of those figures, viz. 1 : 4, so that one wire which is twice the diameter of another, other things being the same, only offers one quarter of the resistance offered by the thin wire. While if we treble the diameter of the wire, or make it three-tenths of an inch, the resistance will be only one-ninth of that of the thinnest wire. As a matter of fact, the thickest of these three wires will weigh exactly nine times as much as the thinnest, there being nine times as much metal in it. We may, therefore, state our law in other words by saying that the resistance of wires uniform in all particulars excepting thickness varies inversely as their weight. Thus, if a mile of copper wire weighs 100 lbs. and has a resistance of 9 ohms and an equal length of similar copper wire weighs 150 lbs. the resistance of the latter will be 6 ohms. Again, the specific resistances of iron and copper are approximately as 6 to 1. If, now, a mile of iron wire, 0·240 of an inch in diameter, has a resistance of 5 ohms, and it is thought for certain reasons desirable to substitute a mile of copper wire having the same resistance, we should have to use wire weighing one-sixth the weight of, or whose sectional area would be one sixth of, that of a copper wire 0·240 of an inch in diameter, because the resistance of a mile of the latter would be only five-sixths of an ohm. The required thickness could be ascertained by rule of three, for if x stands for the required diameter,

$$6 : 1 :: (0{\cdot}240)^2 : x^2,$$

from which we find $x^2 = 0{\cdot}0096$. Therefore x, or the required diameter, is equal to the square root of 0·0096, or 0·098 of an inch nearly.

A conductor offers to the passage of electricity at equal temperatures a constant resistance which is altogether independent either of the electro-motive force or of the strength of the current. That is to say, a wire which offers 10 ohms to the passage of a feeble current, offers precisely the same resistance to a powerful current, except in so far as an increase in the strength of the current involves a corresponding increase in the temperature of the wire, and this increased temperature causes a proportionately increased resistance, as already pointed out.

We come now to the consideration of the laws which determine the strength of a current and of the relationship subsisting between strength and the other attributes of an electric current. The real relationship can, perhaps, be best understood by the aid of a simile. Let us suppose two tanks, one very high up, say three or four hundred feet above the ground, the other raised only a few feet. Let both tanks contain the same quantity of water, and let both of them be supplied with pipes, the one for the upper tank being, however, very much smaller in diameter than that for the lower. On turning the taps the water from the upper tank, although small in quantity, will issue forth with much greater force than that from the lower tank, although the quantity or rate of flow from the lower tank may considerably exceed that from the upper tank. In other words, the pressure in the long small pipe is much greater than in the short but large one, while the quantity of water delivered by the former is considerably less than that delivered by the latter. Pressure in a column of water corresponds with the electro-motive force of a battery, while the volume or quantity of water flowing through the pipe corresponds to current strength. But to pursue the analogy still farther, if the upper tank be raised sufficiently high, the greater pressure so obtained will augment the velocity of the water, and the two tanks will be emptied in the same time. There are two things, then, that govern the quantity of water delivered or the rate of delivery—viz. the pressure, and the size of the pipe, which latter corresponds in electrical considerations with the size of the conductor and consequently with the resistance.

By current strength is meant, therefore, *the amount or volume of electricity passing any point in a circuit at any particular moment.* It corresponds to the rate of delivery of gas or water by a pipe. In a simple circuit it depends upon two things, the electro-motive force of the generator or battery and the resistance of the whole circuit, which comprises the wire and apparatus as well as the battery itself. The practical unit of current strength or rate of delivery is called the ampere, and is that amount of current which is urged through a circuit of one ohm resistance by an electro-motive force of one volt. If this current is maintained for one second, one unit of electrical *quantity* is delivered and this unit is called the coulomb. If a current of half an ampere flows for two seconds, the quantity of electricity delivered is again one coulomb. So also is it if a current of two amperes flows for half a second, so that in every case the rate of flow, or current strength in amperes multiplied into the time in seconds gives us the total quantity of electricity or the number of coulombs. Thus if Q represents the quantity of electricity in coulombs, C the current strength in amperes, and t the time in seconds,

$$\mathrm{Q} = \mathrm{C} \times t.$$

As the quantity of electricity delivered is rarely required to be known, but rather the rate of delivery or flowing, we will deal more fully with the method of ascertaining this rate. In order that this may be more readily understood, we will at once proceed to the discussion of 'Ohm's Law,' which declares that *the current strength varies directly as the electro-motive force, and inversely as the resistance.* This law may be represented by the simple equation—

$$\frac{\text{Electro-motive force}}{\text{Resistance}} = \text{current strength},$$

or,
$$\frac{E}{R} = C.$$

As an example of the relation which the units bear to each other we may take the simple case of a battery having an electro-motive force of one volt and sending a current through a circuit whose total resistance is one ohm. The current strength will then be one ampere, thus :—

$$\frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere},$$

and if this current is maintained for one second, one coulomb of electricity will have passed. By doubling the resistance, we get

$$\frac{1 \text{ volt}}{2 \text{ ohms}} = 0{\cdot}5 \text{ ampere}.$$

Similarly, by doubling the electro-motive force we get, with unit resistance,

$$\frac{2 \text{ volts}}{1 \text{ ohm}} = 2 \text{ amperes}.$$

A little reflection will make evident the subsidiary law that *the current strength is the same in all parts of the circuit*, and does not in any sense vary in different parts of the same circuit. The current strength can easily be supposed to be uniform in a uniform conductor, but if we make up a circuit with wires of different degrees of conductivity, or if we interpose any liquid conductor, the same law holds good, just as would be the case if we were to urge a current of water through a pipe of variable diameter. It is manifest that if a gallon of water enters the pipe in a certain time the same volume must pass out in the same time (supposing the pipe to have been already full), and the same volume must pass every point in the pipe in the same interval of time, although in the thinner or smaller portions of the pipe the water travels faster and generates a little more heat by friction with the sides of the pipe than in the larger sections of it. This latter analogy also holds good with regard to electricity, the thinner wire or poorer conductor will be more highly heated than the thicker or better conductor. It is this fact that makes electric lighting by incandescent lamps possible. It is doubtful whether in the whole range or history of electrical science a law has ever been enunciated so full of truth and of such truly immense importance as that discovered by George Simon Ohm, and we shall find frequent need to refer to it in the succeeding chapters.

For the benefit of those, and our experience teaches us that they are very numerous, who do not understand the full meaning of a simple equation, we may say that if

$$\frac{E}{R} = C, \text{ then } \frac{E}{C} = R, \text{ and}$$

$$E = RC \text{ (or } R \times C).$$

So that, if, of these three quantities, we are told two, we can always readily calculate the third. Thus, with a current of two amperes and an electro-motive force of 10 volts, the resistance will be

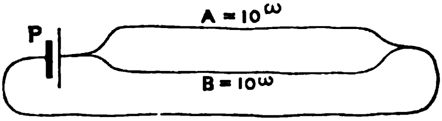
$$\frac{10}{2} = 5 \text{ ohms.}$$

Similarly, if a current of 5 amperes flows through a resistance of 10 ohms, the electro-motive force capable of maintaining this current will be

$$10 \times 5 = 50 \text{ volts.}$$

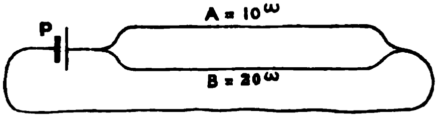
When two or more channels or paths are open to a current of electricity, the current divides between them, just as water or gas in a pipe will divide into any number of branch pipes. If in the case of electrical conductors there are two wires (A and B, fig. 1), between which the current can divide, and if the resistances of the two wires are equal, the current will divide equally between them ; thus, if a current of two amperes flows from the battery P, one ampere will go through each wire. When

FIG. 1.



the resistances are not equal, the current will divide inversely as the resistances; thus, if the resistance of one wire (A, fig. 2) is 10 ohms, and of another (B) is 20 ohms, and a current of three

FIG. 2.



amperes divides between them, two amperes will go through the wire A of 10 ohms and one ampere through the wire B of 20 ohms.

When two or more wires are joined together so that the current divides between them, they are said to be joined up in 'parallel,' and when the end of one is joined to the end of another so that the whole current goes through both wires, one after the other, the wires are said to be joined up in 'series.'

The law for double channels holds equally good for multiple channels. Thus, if there are 10 wires of uniform resistance and a current of 10 amperes divides between them, it will do so equally, so that one ampere will flow through each wire. When the resistances vary, then the current flowing through each wire will vary also, but in the inverse ratio.

When, however, two or more wires are joined up in parallel, a serious alteration is made in the condition of the circuit, for the total amount of current that is produced, whether it be from a primary battery, a dynamo-electric machine, or any other source of electrical energy, will be increased. This increase follows from the fact that when wires are joined up in parallel, their united, or, technically speaking, their joint resistance is less than that of any one of the wires taken separately. The meaning of this will be more readily apparent if a wire is regarded as a conductor rather than as a source of resistance. Thus, if two equal wires lie side by side and the current is allowed to flow through them, the conducting power of the double wire will be twice that of either wire taken separately, in precisely the same way that a water or gas-pipe two square inches in section will transmit twice as much as a similar pipe only one square inch in section. If, therefore, the conductivity of the two wires in parallel is twice that of one of them, their united or joint resistance will be only half that of one of them. Thus, if two wires, each of 100 ohms resistance, are joined to a battery in parallel, their joint resistance will be 50 ohms. Similarly, if ten wires, each of 100 ohms resistance, are joined in parallel, they will offer a joint resistance of 10 ohms. We can, therefore, say that if any number of wires (n) of uniform resistance (R) are joined in parallel, or 'multiple arc,' as the arrangement is sometimes called, then their joint resistance $= \frac{R}{n}$. Suppose, now, that our battery has an electro-motive force of 100 volts, and that its internal resistance is negligibly low, with one wire of 100 ohms joined on we get—

$$\frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere.}$$

With two wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{2} \text{ ohms}} = \frac{100}{50} = 2 \text{ amperes.}$$

This current divides equally between the two wires, one ampere going through each.

With 10 wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{10} \text{ ohms}} = \frac{100}{10} = 10 \text{ amperes.}$$

Whence one ampere will still go through each wire, so that the strength of the current increases in precisely the same proportion as the number of wires. If, however, the internal resistance of the battery is proportionally high enough to necessitate its being taken into account, the reduction of the external resistance will not produce so marked an effect. With a battery resistance of 100 ohms and a single wire of a like resistance we get

$$\frac{100}{100 + 100} = \frac{100}{200} = 0{\cdot}5 \text{ ampere,}$$

and when two wires are joined in parallel we get—

$$\frac{100}{100 + 50} = \frac{100}{150} = 0{\cdot}6\dot{6} \text{ ampere.}$$

With 10 wires we get—

$$\frac{100}{100 + 10} = \frac{100}{110} = 0{\cdot}90 \text{ ampere.}$$

Thus with two wires in parallel a current of 0·33 ampere would flow through each wire, while with ten wires the current strength in each wire would be only 0·09 ampere.

When the parallel circuits are of different resistance, the calculation of their joint resistance involves a little more trouble. Let us suppose two wires joined in parallel, their individual resistances being R_1 and R_2 respectively. As we have already pointed out, resistance is the converse of conductivity. Therefore, R_1 and R_2, representing the resistances, $\frac{1}{R_1}$ and $\frac{1}{R_2}$, will represent their conductivities, whence the united conductivity will be $\frac{1}{R_1} + \frac{1}{P_2}$, which is equal to $\frac{R_1 + R_2}{R_1 R_2}$. This being the joint conductivity, the joint resistance will be $\frac{R_1 \ R_2}{R_1 + R_2}$; thus if $R_1 = 500$ ohms and $R_2 = 1{,}000$ ohms, their joint resistance will be

$$\frac{500 \times 1000}{500 + 1000} = \frac{500{,}000}{1{,}500} = 333{\cdot}3 \text{ ohms.}$$

Briefly put, it may be said that the joint resistance of any two conductors is equal to the product of those resistances, divided by their sum.

Similarly with three (or more) wires of different resistances, their joint conductivity would be

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1 R_2 R_3},$$

whence the joint resistance will be

$$\frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}.$$

If R_1, R_2, and R_3 are 500, 1,000, and 2,000 ohms respectively, their joint resistance will therefore be

$$\frac{500 \times 1{,}000 \times 2{,}000}{(500 \times 1{,}000) + (1{,}000 \times 2{,}000) + (500 \times 2{,}000)}$$

$$= \frac{1{,}000{,}000{,}000}{3{,}500{,}000} = 285{\cdot}7 \text{ ohms.}$$

In the process of electrical testing it is frequently found to be necessary to employ wires of various resistances, either as standards for comparison, or simply for the purpose of placing in a circuit and varying the strength of the current therein. The wires are usually coiled up or wound on bobbins, so as to occupy little space, and are then placed in a convenient case or box; such a set of coils is known as a resistance-box, or rheostat. But if the coils are to be of any real value as standards, great care must be exercised, not only in accurately measuring their resistance, but also in selecting the materials of which they are made, so as to avoid deterioration or change of any kind. The wire must be completely covered throughout by some good insulating substance, to prevent contact between adjacent convolutions, and the material used for this purpose must be able to withstand without change the highest temperature to which it is likely to be subjected; and it must also be incapable of producing any injurious action on the wire. The best insulating material is silk thread, which is wound spirally over the wire in one or two layers.

In selecting the material for the wire itself, several points should be carefully attended to. The metal must be free from any liability to alteration by oxidation, &c. (iron is, therefore, unsuitable). But the most important matter for consideration is the amount of its variation in resistance, with a given change of temperature.

In very important work it is necessary to know the temperature at which a coil was originally measured, and either bring it to that same temperature during the experiment or else make a correction in the result. But either course is somewhat tedious, and in ordinary cases impracticable. In practice the coils are measured at the temperature at which it is probable they will generally be used, say 15° C. (59° F.), and the error lessened by choosing a metal whose percentage of resistance variation with change of temperature is very low.

In addition to changing with any alteration in the temperature of the atmosphere, the wire is more or less heated by the passage of a current itself, so that its resistance may easily alter during a brief or rapidly-performed test or experiment. An examination of the table given on page 19 shows the variation of a platinum-silver alloy to be very small, and it is therefore very extensively employed in high-class apparatus, where the expense becomes a matter of minor importance.

For coils of high resistance it is necessary to choose a metal whose specific resistance is high; otherwise the length of wire would probably be inconveniently great. For low resistances, however, this is not so important; in fact, if a metal of high specific resistance is then used, the wire must be comparatively thick, otherwise it would be so short that very great difficulty would be experienced in making the coils of exactly the right resistance, because a considerable difference would be caused by a small error in the length of the wire. In all cases, however, there is the great advantage in the case of a thick wire, that a given amount of heat raises its temperature to a less extent than it would a thinner wire.

Copper is very unsuitable for resistance coils on account of its great variation in resistance, and, as its specific resistance is low, it would be necessary to employ either a very long or a very fine wire to make a coil of high resistance.

Taking into consideration cost, durability, high specific resistance, and low temperature error, German silver is undoubtedly the most useful material for the purpose; and it is consequently used more frequently than anything else.

A single resistance coil—such, for example, as a standard coil, or one designed for some other special purpose—is, after having been carefully wound on an ebonite or boxwood bobbin, usually mounted in a wooden case or box, furnished with an ebonite cover. Two brass blocks or plates, to which the ends of the wire are soldered, are screwed on to the under side of this cover. Connection with the external circuit is made by means of terminals fixed on the top of the case, and connected electrically with the plates underneath. The form of terminal employed is a matter of more importance than it is usually considered to be, for the contact surfaces at the junction of two conductors, or two parts of the same conductor, always offer some resistance, and if these surfaces are oxidised or dirty, or if the contact is not firm, this resistance will probably be considerable. It is for this reason that the form of terminal or binding-screw shown in fig. 3 is open to serious objection, the contact being as a rule uncertain. Such terminals, in which dependence for good contact has really to be made upon the end of a screw (frequently pointed as if to accentuate the evil),

FIG. 3.

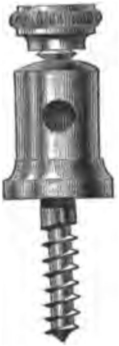
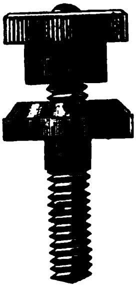


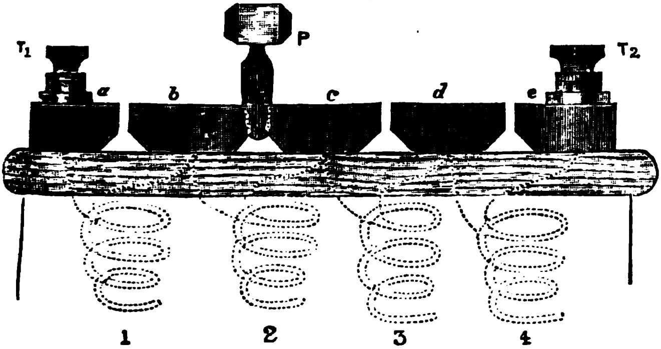
FIG. 4.



should be eschewed, at least for small wires or such as can be readily bent with the fingers. A much better and more reliable terminal is that shown in fig. 4, where the wire is clamped between a fixed base and a screw nut. In tightening the nut, a rubbing effect is produced, which assists in removing any superficial dirt either on the wire or on the terminal, and so tends to ensure good and steady contact. When using this terminal the wire should be bent round the screw shaft, otherwise there will, in tightening up, be a risk of bending the shaft. With the large wires used in electric lighting it is inconvenient and sometimes impracticable to bend the wire. In that case the first-mentioned type of terminal, fig. 3, or a modification of it, is resorted to.

As it more generally happens that a number of coils are required to be so put together that the resistance to be introduced into any particular circuit can be varied at will from the zero to the maximum, special devices have to be employed to obtain this result with the smallest possible waste of time. Fig. 5 shows the best method of casing a number of coils of various resistances; all the coils are joined in series, and the junction of each pair is soldered to the bottom of a brass block, as shown in the figure, great care being taken in winding to ensure the absence of contact or leakage between one portion of the wire and another. The bobbins are fixed to the under side of the ebonite top of the case, the wires being connected to the brass blocks *a*, *b*, *c*, *d*, *e*, which are firmly fixed to the upper side of the ebonite, the adjacent ends of the various blocks being turned out to receive a slightly tapered or conical brass plug. The end blocks are fitted with terminal screws, T_1 and T_2, to which any extraneous wires can be connected. Now, if a wire leading from the copper pole of a battery is joined to a terminal, T_1, and another from the zinc pole to T_2, a current will flow through the resistance box, starting from the left-hand block *a* and passing through the resistance coil No. 1 to the second brass block *b*. Here it has two paths open to it; one through the coil No. 2, of comparatively high resistance, the other through the brass plug P, which has, practically, no resistance at all. All the current will therefore pass by the latter path, and none through the coil, which is said under these circumstances to be 'short-circuited' by the plug P. The

FIG. 5.



current must pass through the coils 3 and 4 before it reaches the terminal T_2.

The brass plug, which should be furnished with an ebonite cap or top, must be carefully tapered to fit the hole *exactly*. Should there be the slightest shake, or should there be any dirt or grit on the blocks or on the plug itself, the contact will be uncertain and the resistance variable. When properly made, the plug, on being inserted with some pressure and a slight twist—say to the right—should fit so thoroughly that on raising it the resistance box should be lifted with it. To remove the plug it should be necessary to first loosen it by giving a slight twist to the left. The lower and the two vertical edges or corners of the blocks should also be filed away to give a larger ebonite insulating surface between the blocks and to allow this surface to be kept clean. This arrangement is necessary in order to prevent, as far as possible, any short-circuit being caused by the accumulation of dust and dirt.

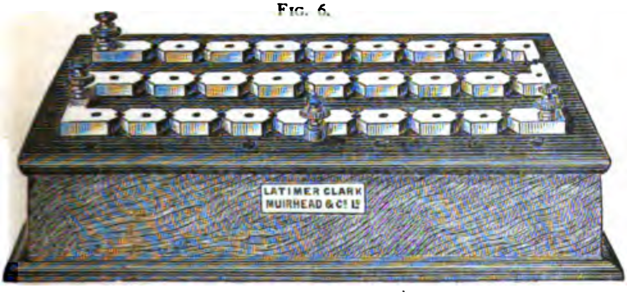
Resistance coils fitted in this way can easily be put in or taken out of the circuit, by withdrawing or inserting plugs between the brass blocks to which the ends of the various coils are soldered. It is hardly necessary to remark that the surfaces of contact should not be lacquered, but should be kept bright and clean.

Resistance coils are frequently used in conjunction with and in the immediate vicinity of delicate measuring apparatus in which a sensitive magnetised needle is employed. If, in such cases, the coils are wound continuously on the bobbin, or in the same manner as a solenoid, an electro-magnetic field of force will be set up immediately a current is sent through the coils, which may be sufficiently strong to impart motion to the needle. If the instrument is being employed to measure the current passing through the resistance, or any effect of that current, serious errors may therefore be introduced by the direct effect of the coils upon the needle. Again, as we shall see later on, it is impossible to start or stop a current in a solenoid suddenly, because work is done and time occupied in establishing, and again in disestablishing, the electro-magnetic field. These are serious defects, and it is fortunate, therefore, that the remedy is simple.

To obviate the difficulty it is only necessary that the wire should be wound 'double'—that is to say, the required length should be measured off and then doubled in the middle, the two halves being wound on together. The meaning of this will perhaps be more apparent on referring to the illustration (fig. 5). The double winding is more easily managed, especially with long coils, by winding the two halves off two separate spools or bobbins and soldering the inner ends together. In either case the two extremities of each coil are brought out together. We have thus two similar helices or solenoids carrying currents equal in strength but opposite in direction. The consequence is that the disturbing effect which would be produced by one solenoid is counteracted or neutralised by the opposite effect which would be due to the other.

When the coils to be enclosed in a box are numerous, it is inconvenient to place them in one long row and thus make a long narrow box. It is preferable to arrange them in two, three, or more parallel rows, connecting these rows together by brass blocks and plugs, as indicated in fig. 6. The centre of each block should also be provided with a tapered hole of the same size as those between the blocks, in order that the plugs may be placed in them when not in use for short-circuiting the coils. It is most important that all the holes and all the plugs should be of exactly the same dimensions, so that the plugs may be interchangeable, or that any one plug may be used for any of the holes. Failing this, considerable inconvenience and risk of error would speedily ensue, for then there would be a particular plug for each hole,

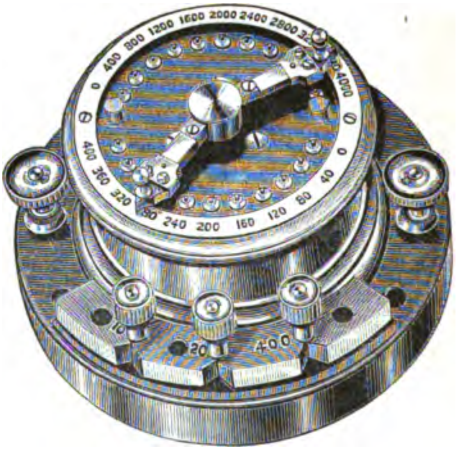
FIG. 6.



and very great difficulty would be experienced in using them and keeping them in their proper places.

Another very useful form of resistance-box or rheostat is shown in fig. 7. The coils are placed inside a round brass case or box provided with an ebonite top and mounted on a mahogany base. Ten coils, each of 40 ohms resistance, are connected to eleven rounded steel points projecting through the ebonite top of the instrument. Ten other coils, each of 400 ohms resistance, are connected to the steel points on the other half of the top side of the ebonite. A number of other coils are connected to the brass blocks fixed on the base of the instrument and resembling those already described; when not required these latter are short-circuited by the usual brass plugs. Supposing the current to enter by the right-hand terminal, it will pass to the nearest brass block, then through the coils of 400,[1] 20, and 10 ohms (or through such plugs as may be inserted between the respective blocks), to the brass block nearest to the left-hand terminal. It then passes by a piece of insulated wire under or in the base of the instrument to the zero stud on the right-hand side, whence it

FIG. 7.



[1] This coil is usually made of 4,000 ohms resistance.

will pass through the 40-ohm coils until it reaches the steel spring carried by the front brass arm, which is movable over these coils and studs. Passing along this arm, which is metallic throughout, it will enter the other movable arm and thence pass to the 400-ohm coils. Leaving at the zero-stud of these 400-ohm coils on the left-hand side, it will pass by a thick wire direct to the left-hand terminal and so to the other part of the circuit. The two arms can be readily moved round over the steel studs or points, so that the range of one arm is from 0 to 400 ohms, and that of the other from 0 to 4,000 ohms. The total resistance in circuit with the arms as shown, and all three plugs *in*, is 3,880 ohms. Although it is a great advantage that the resistance can be very readily varied, the instrument is somewhat objectionable for delicate measuring purposes, as the springs are apt to get weak and the contact unreliable, the resistance then becoming variable.

Another method of casing and joining up resistance coils is shown in figs. 8 and 9. A (fig. 8) is a circular brass plate; *b*, *c*, *d*

FIG. 8.

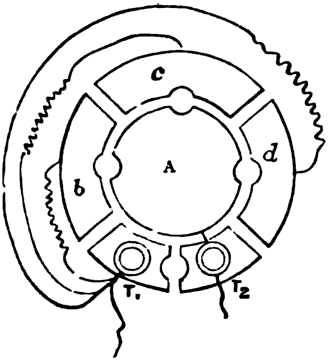
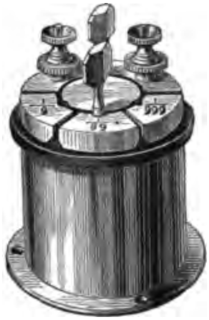


FIG. 9.



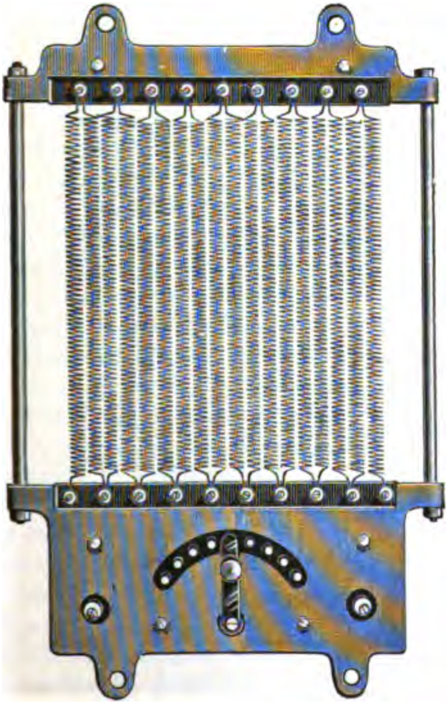
are brass blocks. A tapered hole is provided between each of hese outer plates and the plate A for the usual conical plug. T_1 T_2 are the terminal screws, the latter of which is permanently connected to the brass plate A. One end of each of the three coils is soldered to terminal T_1, and the other end of each to one or other of the outer brass blocks. When it is desired to *insert* in the circuit one of the resistance coils, the plug is placed in the hole which is between the block connected to that coil and the plate A.

Thus the action is the reverse of that described in the last method, for here we insert a plug to insert resistance, removing it to cut out the resistance. Only one coil can, however, be used at a time; and if the plug is placed between terminals T_1 and T_2 the whole box is short-circuited. Fig. 9 shows a box of coils connected according to this method. It is designed for use with a galvanometer as a set of 'shunt coils,' having respectively $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the resistance of the galvanometer. (The nature and applicability of shunt coils will be dealt with in Chapter IV.)

For general use as well as for accurate measurements, the form of resistance-box shown in figs. 5 and 6 should be used. But where a means of rapidly varying the resistance is necessary, the form shown in fig. 7 is often employed. As we have already remarked, resistance varies considerably with temperature, whence every set of coils should have marked on the case the temperature at which they were measured. Then for very accurate tests they may either be brought to that temperature or a correction made in the reading, but in any case it is known whether any great error is likely to be caused by using them at any particular temperature.

It sometimes happens, however, that sets of resistance coils are required merely for the purpose of dissipating a certain amount of electrical energy. For instance, it becomes necessary, when employing some dynamo-electric machines, to reduce the electrical output in response to a correspondingly reduced demand made upon it by the external circuit; and this can be done by joining extra resistance in series with the magnet coils, and allowing some of the power to be expended in heating this extra resistance. In such cases it is not necessary to know exactly the value of the resistance in ohms, but it must be divided into a number of approximately uniform sections, so that its value can be changed gradually. As the currents employed are, in such cases, very powerful, it is important that the coils should be able to withstand a considerable rise in temperature without being in any way injured. The wire must therefore be left bare, so that the heat generated can be dissipated by radiation and convection. Were the wire to be covered with any insulating material, the dissipation by both these processes would be impeded, and there would be the further disadvantage that this sheathing would be sooner or later damaged, if not destroyed. The wire should be of a metal which has a fairly high specific resistance and fusing point, and should not be liable to deterioration by combining with atmospheric oxygen. For these reasons, German silver and tinned or galvanised iron are usually employed, but in special cases platinoid is resorted to. It is essential to select for the supporting frame a material which, while strong, is also non-inflammable and

FIG. 10.



a good insulator, with the smallest possible power of condensing atmospheric moisture upon its surface. In fig. 10 is shown such a set of resistances, constructed by Messrs. Goolden & Co., and suitable for carrying very heavy currents. There are two cast-iron end frames, which are hollow and have slate slabs fitted into them, these slabs being held in position by bolts which pass through both the slate and iron frame. The slabs, projecting inwards from the frames, carry a series of brass bolts and nuts, on to which are fixed the ends of spirals of bare German-silver wire. Slate is an effective insulator for the purpose, and the device of passing the connecting bolts right through it and securing them with nuts, instead of trusting to a screw-thread cut in the material, renders it mechanically satisfactory. The frame is completed and made rigid by a pair of iron rods which are secured to the cast-iron ends. The whole of the spirals are joined in series, the terminals for connection to the external circuit being fixed on to the slate through holes in the bottom end-frame. The left-hand terminal is joined to the bottom of the left-hand spiral, while the right-hand terminal is connected to the lever of a switch which passes over nine contact pillars rising from the slate bed through an opening in the frame. These pillars are connected to the lower junctions of the spirals, and by altering the position of the switch the spirals can be cut in or out of circuit, in pairs, as desired. The iron frames are 12 inches in width, the length being varied up to about 2 feet 6 inches by the employment of connecting rods of different lengths. A set of resistances similar to that illustrated is capable of dissipating about 1,000 watts without undue heating.

We have seen that whenever a current of electricity flows, a certain amount of energy is expended; and it is necessary to be able to measure exactly, the amount of energy so expended in any circuit or in any part thereof. The quantity of work performed in raising a mass of one pound through a difference of level of one foot against the force of gravity, is generally taken as the unit of mechanical energy and is known as the foot-pound. The work done in raising any mass through any height, is found by simply multiplying together the number of pounds in that mass by the number of feet through which it is lifted. Somewhat similarly we can take as the practical unit of electrical energy, the amount expended in transferring a unit quantity of electricity (one coulomb) through a difference of potential of one volt. And by multiplying the number of coulombs which have flowed from one point to another by the difference of potential in volts between those points, we obtain the number of units of electrical energy expended during the passage of the current. The unit of electrical energy, or one coulomb multiplied by one volt, is called the joule. As a simple numerical example we may suppose a current of 10 amperes to flow for 5 seconds, then the quantity of electricity passing through the circuit would be 50 coulombs, and if this current were maintained by a potential difference of 8 volts, the amount of energy expended in that time would be 8 × 50 = 400 joules.

As a rule we wish to know the *rate* at which work is being done in any circuit, rather than the amount which is done in a given time. It is evident that this rate can always be found by dividing the amount of work by the number of seconds taken for its performance, but the same result can be arrived at by multiplying together the potential difference and the rate of transference or flow of electricity, instead of the quantity actually transferred in a given time. Now the rate of flow of electricity is what we know as the current strength, which is measured in amperes. Therefore, if the difference of potential in volts between any two points is multiplied by the resulting current in amperes, the product gives the rate at which energy is being expended, or the rate of working between those two points. The unit rate of working or the unit of *power* is called the *watt*—that is to say, 1 ampere × 1 volt = 1 watt. Therefore, if a difference of potential of 20 volts between the ends of a wire maintains a current of 3 amperes, the rate of working is 3 × 20 = 60 watts.

It is desirable that the relation between mechanical and electrical rates of working should be understood. The mechanical unit is termed the 'horse-power,' and is equal to that rate of working which, if continued for one minute, would expend 33,000 foot-pounds of energy, or raise 33,000 pounds one foot in height. One horse-power is equal to 746 watts, so that, having calculated the number of watts absorbed in any particular case, on dividing this number by 746 we get the rate of working, or rate of loss of energy, expressed in horse-power. This power of 746 watts is, therefore, frequently referred to as the electrical horse-power.

Subsequent to the passing by Parliament of the Bill making the Board of Trade the arbiters of the destinies of electric lighting concerns, the Board selected a larger practical unit of electrical power. It is known as the Board of Trade unit, and is equal to 1,000 watts, or the power expended by 1,000 amperes at a potential difference of 1 volt. A convenient name for this unit is the kilo-watt.

The units described in this chapter are those which are, and which will continue to be, employed in practice by the electric lighting engineer. No effort should therefore be spared to master the simple relation existing between the ampere, volt, ohm, horse-power, &c.

But it is advisable to know the method by which the various electrical units have been evolved, for they have not been selected arbitrarily, like the pound, yard, and gallon, but are built up on the fundamental conceptions of length, time, and quantity of matter, and are inseparably linked together. Perhaps the simplest measurable quantity which we can conceive is that of length, and in deciding upon a unit of length an effort was made to select some unalterable natural distance. The length of an earth quadrant—that is, the distance from the equator to the pole along a meridian—was agreed upon, and one ten-millionth part of this taken as the practical standard of length, and called a metre. The original measurement of the earth quadrant proved to be considerably in error, and consequently the simple relation between it and the metre was upset. But the metre thus determined is retained as the standard of length, and one hundredth part of this length, called one centimetre, is taken as the basis of the units upon which the system now to be briefly described has been reared. A square centimetre is the area contained in a square each of whose sides is one centimetre, and a cubic centimetre is the volume contained in a cube each of whose edges is one centimetre in length.

The next unit required is that of mass, or quantity of matter, and it should be remembered that the force of gravity acts upon every body in exact proportion to its mass, or the quantity of matter in it, independently of its size; therefore, what we know as the weight of any substance is exactly proportional to its mass. The unit of mass is called the gramme. It is equal to the mass contained in a cubic centimetre of pure water at its maximum density, i.e. at 4° Centigrade.

The third unit, that of time, is called the second. It is the length of time known in England by that name, and is the 86,400th part of a mean solar day.

The great value of a system built upon such units as those described is that it is always possible to recover any one of them, and so reconstruct or verify the system if necessary, although the process is no doubt difficult and tedious. The term 'absolute' has been applied to such a system, but it is not easy to see the precise application of the word here. It is usual, and certainly far better, to refer to it as the centimetre-gramme-second, or the C.G.S., system.

The next conception in order of simplicity, is that of the rate at which a mass of matter changes its relative position, or the velocity with which it moves. Velocity is estimated by dividing the distance in centimetres through which a body moves by the time in seconds taken to travel that distance. The unit is a velocity of one centimetre per second.

A mass of matter cannot, by any property belonging to it, change its position or its state of rest or motion, by itself. That which is competent to move, stop, or vary the motion of a mass of matter is called force, and the greater the force, and the longer the time during which it acts, the greater will be the increase or decrease in the velocity of a given mass. The unit of force is called the dyne; one dyne is that force which, by acting upon a mass of one gramme during one second, can impart to it a velocity of one centimetre per second.

When the position of a body is changed in opposition to any resisting force, work is done or energy expended, the amount being estimated by multiplying together the force overcome and the distance through which it is overcome. The unit of work is called the 'erg,' and is that work done when a force of one dyne is overcome through a distance of one centimetre; the energy expended is in every case equal to the work done, therefore the erg is also the unit of energy. We have seen that the practical unit of work, or expenditure of energy, is the joule; and one joule is equal to ten million ergs. Consequently, the practical unit of power, or rate of doing work, called the watt, is equivalent to ten million ergs per second.

Current strength is measured by the quantity of electricity which flows past any point in a circuit per second. The unit is that current strength which, when one centimetre of its path—that is to say, one centimetre of the conductor carrying the current—is curved into an arc of one centimetre radius, exerts a force of one dyne upon a unit magnet pole placed at its centre. The conditions of this unit will, however, be better understood after studying Chapter IV. The practical unit which is called the 'ampere' is equal to one-tenth of this so-called 'absolute' unit.

The unit quantity of electricity is that quantity conveyed by unit current in unit time. The practical unit, the coulomb, is therefore also one-tenth of the absolute unit.

The unit difference of potential between two points exists when one erg of work has to be performed in urging one unit of electricity against the electric force, or when one erg is expended by the flow of one unit of electricity from one point to the other. The volt or practical unit is 100,000,000 times the absolute unit.

Unit resistance exists when unit difference of potential causes unit current strength to flow through it. It follows, therefore, that the ohm is equal to 1,000,000,000 absolute units. The units which chiefly claim our attention are those of current, quantity, potential difference, and resistance. It is not possible to provide an invariable physical standard of either of these except resistance, which fact to a certain extent increases the importance attached to the unit of resistance. As has been pointed out, a reliable physical standard, in the form of a column of mercury of certain dimensions, has been selected to represent the ohm.

CHAPTER III.

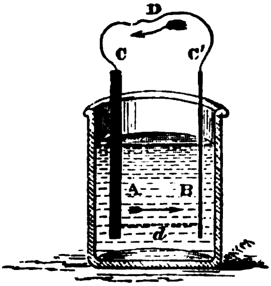
PRIMARY BATTERIES.

A CURRENT of electricity can be maintained in a number of ways. One of these is by means of primary cells. A primary cell consists of a vessel containing a saline or acidulated solution, in which are immersed two solid conducting bodies, one of which is more assailable than the other by the liquid. When two or more cells are joined together to increase the effect, the combination is known as a battery.

Primary cells can be divided into two classes, viz. (*a*) single-fluid, or those in which only one solution is used, and (*b*) double-fluid, or those in which two solutions are employed.

The single-fluid cells are typified by the 'simple cell,' which was referred to on page 2, and which consists of a glass or earthenware vessel (fig. 11) nearly filled with water acidulated with a small proportion of, say, sulphuric acid, and containing a piece of zinc, A, and a piece of copper, B. On connecting the plates by a piece of wire, c′ c, and thereby causing the current to flow, the surface of the zinc is attacked and sulphate of zinc is formed, hydrogen gas being liberated at the surface of the plate B.

FIG. 11.



This reaction may be represented by an equation, thus :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{SO_4H_2} = \underset{\text{Sulphate of zinc.}}{SO_4Zn} + \underset{\text{Hydrogen.}}{H_2}$$

No chemical effect whatever is produced on the surface of the plate B, and it may here be noticed that the plate which is more or less dissolved, is called the positive plate, the other being called the negative plate. Chemical action may be supposed to take place throughout the entire length of the liquid or the distance between the plates, but it is not manifest except at the surfaces of the plates, and, for convenience' sake, it may be said to commence at the positive plate—that is to say, the acid particles, or, more correctly speaking, molecules in contact with the zinc plate may be assumed to be the first decomposed, the hydrogen thus liberated attacking the next succeeding acid molecules in a similar manner. Hydrogen is again liberated, which again in its turn decomposes the adjacent acid molecules. A series of decompositions and recompositions is thus propagated throughout the entire liquid by a process of repetition, molecule for molecule, resulting finally in the deposition of the free hydrogen on the copper or negative plate. As the hydrogen thus deposited does not enter directly into chemical union with any of the simple metals, it remains in the gaseous state. The resultant changes present the appearance of the acid alone being affected, while the water remains constant and unchanged. The action may be expressed in chemical formulæ, thus :—

Before action.

$$\underset{\text{Zinc or +}}{|}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \underset{\text{Copper or −}}{|}$$

In action.

$$\underset{\text{Zinc or +}}{|}\ \overline{SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2}\ \underset{\text{Copper or −}}{|}$$

The hydrogen is here released in a definite ratio to the amount of zinc dissolved. In fact, we may take it as an established law that the ratio between the weight of zinc dissolved and that of the hydrogen, &c., released by the passage of the current, is invariable, and that this ratio is dependent upon their respective electro-chemical equivalents.

We see by the above equation that for every atom or equivalent of zinc dissolved or converted into sulphate of zinc, two atoms of hydrogen are liberated. An atom may be defined as the smallest possible quantity of any substance capable of entering into or passing out of combination ; and it will be seen, on referring to the accompanying table of atomic weights, or of the relative weights of individual atoms of some of the more important substances, that an atom of hydrogen weighs less than one of any other substance :—

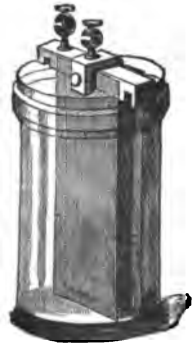
TABLE OF ATOMIC WEIGHTS AND EQUIVALENTS.

Elements	Symbol and Valency	Atomic Weight	Chemical Equivalent	Electro-chemical Equivalent (Milligrammes per Coulomb)
ELECTRO-POSITIVE.				
Hydrogen . . .	H^1	1·	1·	·010384
Potassium . . .	K^1	39·04	39·04	·40539
Sodium . . .	Na^1	22·99	22·99	·23873
Aluminium . . .	Al^3	27·3	9·1	·09449
Magnesium . .	Mg^2	23·94	11·97	·12430
Gold	Au^3	196·2	65·4	·67911
Silver	Ag^1	107·66	107·66	1·11800
Copper (Cupric) . .	Cu^2	63·	31·5	·32709
,, (Cuprous) .	Cu^1	63·	63·	·65419
Mercury (Mercuric) .	Hg^2	199·8	99·9	1·03740
,, (Mercurous) .	Hg^1	199·8	199·8	2·07470
Tin (Stannic) . .	Sn^4	117·8	20·45	·30581
,, (Stannous) . .	Sn^2	117·8	58·9	·61162
Iron (Ferric) . .	Fe^3	55·9	18·64	·19356
,, (Ferrous) . .	Fe^2	55·9	27·95	·29035
Nickel . . .	Ni^2	58·6	29·3	·30425
Zinc	Zn^2	65·	32·5	·33696
Lead	Pb^2	206·4	103·2	1·07160
ELECTRO-NEGATIVE.				
Oxygen . . .	O^2	15·96	7·98	·08286
Chlorine . . .	Cl^1	35·37	35·37	·36728
Iodine	I^1	126·53	126·53	1·31390
Bromine . . .	Br^1	79·75	79·75	·82812
Nitrogen . . .	N^3	14·01	4·67	·04849

It is in consequence of this fact that hydrogen is taken as the standard in calculating the atomic weights of the various simple or elementary bodies. It will also be observed that an atom of zinc weighs sixty-five times as much as an atom of hydrogen. The meaning of the equation, therefore, is that for every sixty-five parts by weight of zinc dissolved, two parts by weight of hydrogen are liberated ; consequently, if we again regard the relative deposition of hydrogen as the standard, the weight of zinc dissolved will be 32·5 times as much, or, in other words, the electro-chemical equivalent of hydrogen being unity, that of zinc is 32·5. The equivalents of the other elementary bodies enumerated in the table have been calculated in a similar way.

The liberated hydrogen, in consequence of its low specific gravity, exhibits a tendency to rise through the water and escape into the air. Only a portion, however, of the gas escapes in this way, a large proportion adhering to the copper plate and forming, as it were, a gaseous film over the metallic surface. This accumulation, due to a variety of causes, is facilitated by the opposite polarities or electrical conditions of the copper and hydrogen which cause a mutual attraction to set in. There is a double effect of the accumulation which soon becomes apparent, for a gradual diminution in the current sets in, consequent first on the decrease in the copper surface exposed to the liquid (which involves a proportional increase in the internal resistance of the cell), and, secondly, on the tendency on the part of the positively electrified hydrogen film to set up a contrary current. Free hydrogen is, in fact, more positive than the zinc itself. When this condition is arrived at, the cell is said to be polarised. The effect of the passage of a current being, therefore, a reduction of the electro-motive force of the cell, such a combination is manifestly useless for purposes requiring a continuous and uniform current.

FIG. 12.



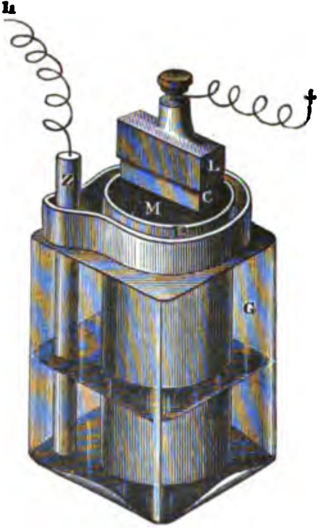
To overcome this really strong objection Smee constructed a cell (fig. 12), the peculiarity of which consisted in the nature of the surface of the negative plate. It had been ascertained that a smooth surface engenders a much more rapid accumulation of hydrogen than does a roughened surface. Accordingly, he used for his negative plate a thin sheet of silver covered with platinum in a state of very fine division, so that an irregular surface was produced. So treated the plate is known as platinised silver. There are two zinc plates connected to the same terminal, but placed one on each side of the silver, the solution being 1 of acid to 10 of water. This cell, which is still largely used, is considerably more lasting than the simple cell; the unevenness of the negative surface facilitates the ascension of the hydrogen particles more nearly in proportion to the rate of production. It has also a higher electro-motive force because of the substitution for copper of a more electro-negative plate. This form of battery is useful where currents are required for brief periods, but it is far from being a constant cell, that is, one which yields a *continuous and uniform* current. When, however, the cell is put together of abnormally large proportions, it approximates more nearly to the condition of a constant cell, and is used as such by many electroplaters.

The Smee cell is capable of being manufactured in a very compact form. The silver foil is fixed in a frame made by fastening together four pieces of wood about half an inch square in section, the upper edge of the foil being connected to a brass terminal on the top of the frame. The plates of zinc, a trifle larger than the foil, are placed against the two sides of the frame and all three are then clamped together by a strong brass terminal or clamp which is placed in contact with the zincs. The advantage gained by this form of construction is that the internal resistance of the cell is very low ; first, because the two zinc plates are opposite to the two sides of the foil, and, secondly, because the distance between the foil and the zincs is very small. The wooden frame is necessary, to support the thin silver foil and to prevent it touching either of the zinc plates. Were there any other simple means of preventing this contact, the frame might be dispensed with.

There is in use at the Royal Observatory at Greenwich a remarkably simple and useful modification of the Smee cell. It consists of a plate of zinc and a plate of good gas-retort carbon, the upper portion of which is rendered non-porous by immersion in hot paraffin wax. The solution is one of dilute sulphuric acid, the acid being, however, very pure. The hydrogen bubbles can be seen rising freely through the solution, instead of adhering to the uneven surface of the carbon. The resistance of the cell is very low, and its electro-motive force, after a few minutes, remains steady at about half a volt.

A far more important cell than the Smee is the Leclanché (fig. 13), in which a zinc rod, z, is used as the positive plate, while the negative plate C takes the form of a rod or slab of gas carbon, or of prepared carbon. The gas carbon is one of the by-products in the manufacture of gas, and is formed by the condensation of a portion of the carbon in the cooler portions of the retort. The prepared carbon is made by subjecting to considerable pressure, at a high temperature, a mixture of powdered carbon and some treacly substance which is employed for cementing the carbon particles. The carbon plate is placed inside a vessel of porous (unglazed) earthenware, which is then filled with a mixture of crushed, but not powdered, carbon and black oxide of manganese. The latter should be of the 'needle' or granular form, care being taken to exclude powder or dust. The outer vessel, G, is generally of glass, which enables the condition of the cell to be observed without removing any of the parts. The liquid consists of a saturated solution of sal-ammoniac, or chloride of ammonium, the porosity of the inner jar allowing the solution to diffuse itself somewhat freely, and so to moisten the mixture of carbon and black oxide.

FIG. 13



The zinc combines with the chlorine of the sal-ammoniac, forming zinc chloride, simultaneously releasing hydrogen and ammonia, which latter dissolves in the water until a saturated solution is obtained—that is to say, until the solution holds as much as it can support—after which it escapes as a gas readily recognised by its characteristic odour. It may, however, be remarked that water is not saturated with ammonia until it has absorbed 727 times its volume of the gas at a temperature of 15·5° C. or 60° F. The hydrogen, so far, remains free, as shown by the equation :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sal-ammoniac.}}{2NH_4Cl} = \underset{\text{Zinc chloride.}}{ZnCl_2} + \underset{\text{Ammonia.}}{2NH_3} + \underset{\text{Hydrogen.}}{H_2}$$

It is, however, ultimately released inside the inner vessel, and there it deprives the manganic oxide of some of its oxygen, forming water and sesqui-oxide of manganese, thus :—

$$\underset{\text{Hydrogen.}}{H_2} + \underset{\substack{\text{Manganic}\\ \text{oxide.}}}{2MnO_2} = \underset{\text{Water.}}{OH_2} + \underset{\substack{\text{Sesqui-oxide of}\\ \text{manganese.}}}{Mn_2O_3}$$

The entire action may be represented by a single equation, thus :—

$$Zn + 2NH_4Cl + 2MnO_2 = ZnCl_2 + 2NH_3 + OH_2 + Mn_2O_3.$$

The action so represented is, of course, similar to that of the simple cell or the Smee, in so far as concerns the propagation of the series of decompositions and recompositions. There is, however, a subsequent or secondary reaction between the zinc chloride and the other constituents of the solution, resulting in the formation of what are called double salts, which tend to impede the efficient working of the cell.

One great advantage this battery has over most, if not all other forms, is that it does not in any way deteriorate by inactivity, unless the evaporation of the water can be regarded in this light, but even that may be prevented. It is no unusual experience for these cells to remain in work for upwards of a year without the necessity for any attention whatever, and even then it is probable that a jug of water is all that is required. It will be seen, from a study of the equations given above, that the working of the battery results in the gradual absorption of the zinc, and the decomposition of the sal-ammoniac, &c., which accordingly require replenishing at times. A whitish-yellow turbidity in the solution indicates the presence of an excessive amount of zinc chloride in proportion to the amount of sal-ammoniac, which latter should then be increased, although it would be as well to remove a portion of the solution and then fill up with water before adding the sal-ammoniac.

Considerable care is taken in the construction of this cell. As both sal-ammoniac and ammonia are corrosive and attack copper, brass, &c., all the exposed metallic surfaces should be well served with gutta-percha, pitch, paraffin wax, or some other non-corrosive and impervious material.

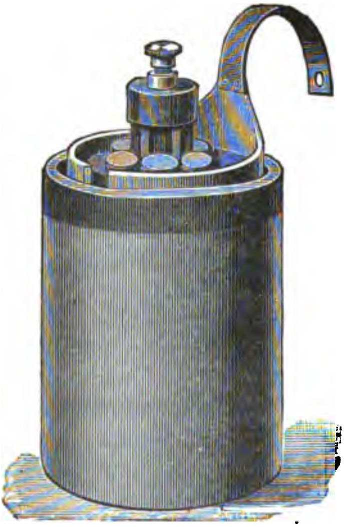
Where the batteries are made in very large quantities, it is the practice to drill two small holes through the upper extremities of the carbons, and, after raising these ends to a high temperature, to dip them into melted paraffin wax. They are subsequently placed into a mould containing molten lead, a terminal or binding-screw being cast into this leaden cap at the same time. The function of the wax is to close the pores in the upper portion of the carbon, and so to prevent the ammoniacal solution from creeping up to the terminal or leaden cap. Lead is interposed between the waxed carbon and the brass terminal because it is the least assailable of the ordinary metals. Pitch is run over the carbon-manganese mixture to keep the mixture and the carbon rod in position, and to form an impervious covering, holes being made in it, however, to permit any hydrogen or other gases that may be formed to escape. The upper parts of the porous pot, and the zinc rod and the connections, are likewise coated with pitch. Sometimes an india-rubber cover is made to fit over the top of the battery, so as to hold the porous pot and the zinc permanently in position, and to prevent the evaporation of the water.

The electro-motive force of this battery is nearly twice that of the Smee, while, owing to the large surface exposed, more particularly at the negative plate, the internal resistance is also low. The cell is, however, only useful for sending occasional or intermittent currents, such as are required in electric-bell work. In fact, the chief objection to this battery is the great rapidity with which it polarises and so becomes temporarily useless, owing probably to the fact that hydrogen is liberated faster than the manganic oxide can be decomposed. Consequently, a more or less perfect film of hydrogen is deposited over the surface of the carbon. That this is the case is in a measure demonstrated by the fact that if the cell is allowed to stand idle for a brief interval of time it will again yield its full current. This intermittent action obviously limits very materially the cell's sphere of usefulness. The defect, although very marked when the resistance of the circuit is very low, is reduced to a minimum when the resistance is high, because the current is then feeble and the chemical reactions proportionately less. The fact that the constituents of the cell remain inactive when the cell is idle, is a point of very considerable importance, and is a very useful feature, for it means that there is no wasteful action in the battery, such as we shall find there is in practically every other type of battery—at least, in every battery in which an acid plays a part. Cleanliness is, however, absolutely necessary in dealing with the Leclanché, or, indeed, with any other form of battery, and it is essential that the containing vessel, whether of glass or earthenware, should be kept dry externally. The latter desideratum is usually accomplished by coating the upper portion of the outer surface of the vessel with pitch or some other such substance as will not permit the liquid to 'creep' over its surface, for the salt (sal-ammoniac) has a strong tendency to crystallise out. Should the solution be allowed to creep, we have to contend not only with the waste of salt so occasioned, but also with the 'leakage' of electricity that would take place over the moistened external surface.

There is a modification of the Leclanché which is of some importance and which is known as the 'agglomerate' Leclanché. The negative element consists of a carbon plate or block, having in contact with it blocks of agglomerated carbon and manganese. The latter are prepared by intimately mixing 40 parts of manganic oxide, 55 parts of gas carbon, and 5 parts of gum lac resin, and submitting the mixture, placed in a steel mould, to a temperature of 100° C., applying at the same time considerable hydraulic pressure. The result is a solid compact mass, and, as the chief function of the porous-pot in the older type is to support the mixture of crushed carbon and manganic oxide, it is apparent that that vessel, which materially increases the internal resistance of the cell, can be dispensed with. India-rubber bands placed round the agglomerated blocks (which in their turn embrace the carbon block), keep the whole of the compound negative element together. In the earlier forms of agglomerate cell, rectangular blocks of agglomerated manganic oxide and carbon were held against the two faces of a flat plate or block of carbon, and the india-rubber bands holding the three blocks together were specially made so as to hold also the zinc rod, which was of the usual type.

But a much better form is that known as the 6-block agglomerate (see fig. 14), which is very extensively used. The negative element consists of a block of carbon with six fluted sides, which is capped with lead and fitted with a terminal after the top of it has been steeped in hot paraffin wax. In each of the sides is laid a round stick of the agglomerated carbon and manganic oxide, the whole being wrapped round with a piece of coarse canvas, and held in position by a couple of stout india-rubber bands. The canvas does not, of course, prevent intimate contact between the rods and the solution, nor does it appreciably increase the internal resistance of the cell, its function being simply to prevent pieces of the agglomerate rods falling out and 'short-circuiting' the cell, by joining the positive and negative elements together. Instead of employing a zinc rod for the positive element, a large piece of sheet zinc (about $\frac{1}{8}$ inch thick) is rolled into a cylinder, the approaching edges being, however, kept a quarter of an inch or so apart to allow of the free circulation of the solution. In consequence of the very large increase in the amount of surface thus exposed to the liquid, the internal resistance is very considerably reduced, polarisation being also to a great extent prevented or at least impeded. The current produced is much more uniform than that from the old type Leclanché. As a matter of fact, when employed upon circuits offering high resistance, an almost constant current is produced, and, as the cell is pre-eminently a clean one, as the cost of maintenance is very low, and as there is a total absence of wasteful action when the cell is idle, it is rapidly gaining ground and driving out of the market many other types of cell, such as the Daniell and the Bichromate (to be presently described). In fact, for ordinary work on circuits of high resistance, or even for hard but intermittent work on circuits of low resistance, we know of few, if any,

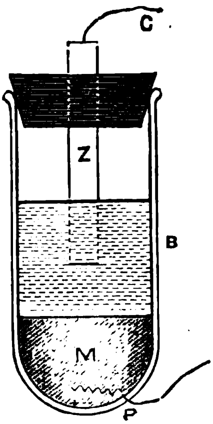
FIG. 14.



serious objections to its use, while, on the other hand, it possesses the important advantages above enumerated.

The 'Standard' cell (fig. 15), invented by Mr. Latimer Clark, is an important one. It is designed solely as a standard of electro-motive force, and is largely employed for purposes of measurement. It is made in a small glass vessel, such as a short wide test-tube, a layer of pure distilled mercury, M, being employed as the negative plate, which covers the bottom of the glass vessel to a depth of half an inch or so. Over this is placed the 'liquid' or electrolyte, which consists of a thick paste, B, made by mixing mercurous sulphate with a saturated solution of zinc sulphate. The positive element is a rod of pure distilled zinc, Z, which dips into the paste. It is usual to seal the battery by means of paraffin wax or india-rubber, S. Connection is made with the zinc by means of a copper wire, C, soldered to the upper end of the zinc rod passing through the wax or rubber stopper. A platinum wire, P, fused into the bottom of the vessel, makes contact with the mercury.

FIG. 15.

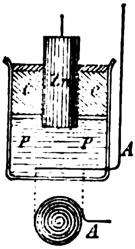


It is highly essential that the constituents of the cell should be absolutely pure, hence the necessity for re-distilling the zinc and mercury. The mercurous sulphate can be made by dissolving pure mercury, placed in excess, in hot pure sulphuric acid. The sulphate is an insoluble white powder, and should be well washed with distilled water before it is mixed with the zinc sulphate, to remove any trace of the mercuric sulphate or of free acid. The mercuric contains a larger proportion of mercury than the mercurous sulphate, and, on the addition of water, imparts to it a yellowish tinge.

The chemical action which takes place during the passage of a current is to decompose the mercurous sulphate, adding the mercury released to that already in the vessel, an equivalent of zinc being dissolved off the positive rod.

The electro-motive force of this cell is 1·435 volts and is exceedingly uniform, providing only a high external resistance, not less than 1,000 ohms, is employed. If the resistance of the circuit is low, the current becomes proportionally strong. The mercury salt is not then capable of being decomposed at a corresponding rate, whence polarisation sets in and the electro-motive force falls in consequence. The electro-motive force also decreases with an increase of temperature, the rate being about 0·08 per cent. per degree Centigrade.

FIG. 16.



The commercial form of Clark cell constructed after the plan of Dr. Muirhead is illustrated in fig. 16. Instead of using a layer of mercury, the platinum electrode A, fused through the glass-containing vessel, is made of a long piece of wire which is coiled into a close flat spiral and coated with mercury, either by heating and then immersing it in a mercury bath, or by heating the mercury and the platinum together. The spiral is then embedded in the paste, composed of pure mercurous sulphate and a saturated solution of pure zinc sulphate, *p*. The pure zinc rod, *Zn*, is dipped into the paste, and a cement stopper, *c*, holds the whole firmly together, so that the cell is made more portable than that shown in fig. 15, which has the disadvantage that the constituents of the cell are liable to become mixed if it is not used very carefully. The mercury deposited on the platinum spiral is sufficient to form the negative element or 'plate,' so that a layer of mercury is not really necessary.

FIG. 17.

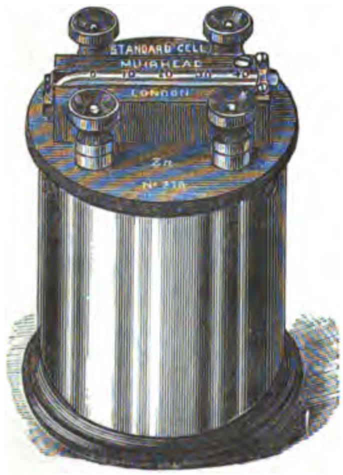
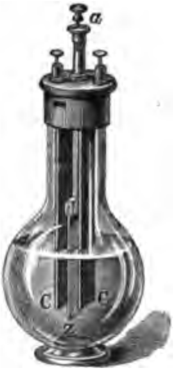


Fig. 17 shows the method employed for casing in. A cylindrical brass case with an ebonite cover is used, and contains two cells which can be balanced one against the other to test their relative electro-motive force, or they can be used together and give a double electro-motive force. A thermometer is likewise provided, the bulb being inside and the tube bent so as to lie over the scale on the cover. This is an important, though simple innovation, and assists in the avoidance of an error due to a varying temperature.

The only other form of single-fluid battery which we shall notice is that in which a solution of bichromate of potash is employed, and which is generally made in the form shown in the diagram (fig. 18). It consists of an alternation of zinc and carbon plates (always one more of carbon than of zinc), placed in a glass vessel containing the solution. The carbons are all connected with one terminal so as to give a large negative surface, and all the zincs with another to oppose a large positive surface to the solution. In most cases the zincs are attached to a metal rod, *a*, which slides in a hole in the cover, so that by raising the rod the plates can be readily removed from the liquid and the wasteful consumption of the zinc and bichromate of potash which would otherwise take place when the cell is idle prevented.

FIG. 18.



The solution consists of 1 part by weight of bichromate of potash, 2 parts of good sulphuric acid (of 1·8 specific gravity), and 12 parts of clean water. The bichromate of potash is first pulverised and then added slowly to the acid, stirring all the time. This converts the bichromate of potash into chromic anhydride and potassic sulphate, which precipitates in a beautiful crystalline formation, the chemical reactions being indicated by the equation :—

$$\underset{\text{Bichromate of potash.}}{K_2Cr_2O_7} + \underset{\text{Sulphuric acid.}}{7SO_4H_2} = \underset{\text{Chromic anhydride.}}{2CrO_3} + \underset{\text{Potassic sulphate.}}{K_2SO_4} + \underset{\text{Water.}}{OH_2} + \underset{\text{Sulphuric acid.}}{6SO_4H_2}$$

Water is then added slowly, when the crystals are dissolved and the chromic anhydride converted into chromic hydrate or acid (H_2CrO_4) by the absorption of water, a quantity of the water being taken up, with the usual result that follows the admixture of sulphuric acid and water—viz. the evolution of a considerable amount of heat. The energy with which the acid unites with the water is very great, and it is this that necessitates the slow addition of the latter. If poured on too abruptly there is considerable danger of the mixture being ejected from the vessel and scattered about the person or on anything that may be near. As the acid is exceedingly corrosive, it is impossible to take too much precaution when adding the water. In ordinary cases where the acid and water are to be mixed it is by far the safer plan to add the acid to the water, as the former will then find plenty of the latte to satisfy its almost insatiable thirst.

When the solution of the crystals is completed and when the liquid has cooled down to the ordinary temperature, it is ready for use. On completing the circuit and allowing the current to flow, the zinc is dissolved, forming zinc sulphate, and the chromic acid is converted into chromic sulphate, water being liberated The reaction may be expressed by the equation :—

$$3Zn + 6H_2SO_4 + 2H_2CrO_4 = 3ZnSO_4 + 8OH_2 + Cr_2 3(SO_4$$

Zinc. Sulphuric acid. Chromic acid. Zinc sulphate. Water. Chromic sulph

This battery has a high electro-motive force, while its resistanc is very low. It yields, therefore, a considerable current, whic does not, however, last long, rarely more than an hour or so because of the rapidity with which the cell becomes polarised On the other hand, when only used occasionally, the same solutio will last for a very long time. As there is a tendency, by secondar chemical reactions taking place between the various constituent of the cell, to form hard crystals of a double salt (known as chrom alum) which at times cause a fracture of the jar, it is advisable t avoid square or flat cells for this battery. As we shall presentl see, a modification is extensively used on account of its hig electro-motive force, its low internal resistance, and its approximation to constancy.

We come now to consider the double-liquid batteries, the great aim of which is to obtain constancy, even if at the loss of a little power. The chief obstacle to constancy, we have seen, is the accumulation of hydrogen on the negative surface, which hydrogen must therefore be absorbed. Daniell, in 1836, was the first to achieve this object, which he did by using a metallic salt in the neighbourhood of the negative plate, separated from the zinc and acid solution by means of a porous division which, on being moistened, allowed the current to pass through it, but which at the same time prevented, or rather impeded, the intermingling of the two solutions. The conception of a porous division was certainly a brilliant idea, but so also was that which determined the kind of solution which was to surround the negative plate. This liquid contains a large quantity of the very same metal as that of which the plate itself is constructed, and it is due in a great measure to this fact that the Daniell cell stands alone, and pre-eminently so, as *the* constant cell. The cell is put together in a great variety of shapes and patterns, varying with the purpose to which it is intended to be applied. It consists essentially of an outer porcelain or other non-porous vessel, containing the zinc. Inside this is placed an unglazed earthenware vessel, which contains a piece of thin sheet copper. The porous vessel is nearly filled with copper sulphate (known more generally as bluestone), and water is poured on till the level is about the same as that in the outer vessel, which contains a solution of one part sulphuric acid, or zinc sulphate, with 12 to 20 parts of water.

The chemical reactions which take place in the Daniell cell are of a very simple character. On completing the circuit the zinc enters into action with the sulphuric acid and forms sulphate of zinc ($ZnSO_4$), releasing free hydrogen (H_2), in precisely the same way as in the simple cell. This hydrogen is not, however, liberated on the surface of the negative or copper plate, but at or near the porous partition where the two liquids meet. The hydrogen coming into the presence of the copper sulphate solution, proceeds at once to displace the metal from its combination, setting it free as metallic copper, and taking its place to form a new equivalent of sulphuric acid. The liberated copper acts in a manner very much akin to that of the free hydrogen in the acid solution—that is, it breaks up the next molecule of copper sulphate, and produces a new molecule of the same compound by replacement, and so on until the surface of the negative plate is ultimately reached, on which is deposited the finally released copper particle.

A little reflection will reveal to the student something of the greatness of the advance thus made by Daniell. In the first place, we find the released hydrogen, which was the great drawback in the simple cell, taken up entirely by a very easily decomposable salt, and thus prevented from polarising the battery. Furthermore, instead of the deposition of the foreign hydrogen film on the copper plate, copper purer than can be obtained by any other simple process is deposited. In fact, a similar process is employed commercially for the extraction of copper from its ores, and for the refinement of comparatively impure bars. The action that takes place from the zinc to the copper surface may be expressed thus :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\substack{\text{Sulphuric}\\ \text{acid.}}}{SO_4H_2} + \underset{\substack{\text{Copper}\\ \text{sulphate.}}}{SO_4Cu} = \underset{\substack{\text{Zinc}\\ \text{sulphate.}}}{ZnSo_4} + \underset{\substack{\text{Sulphuric}\\ \text{acid.}}}{SO_4H_2} + \underset{\text{Copper.}}{Cu}$$

Or showing the effect on a few of the intermediate molecules :—

Before action.

$$\underset{\text{Zinc.}}{\lceil} \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2} \underset{\substack{\text{Porous}\\ \text{partition.}}}{\mid} \overline{SO_4Cu}\ \overline{SO_4Cu}\ \overline{SO_4Cu} \underset{\text{Copper.}}{\mid}$$

In action.

$$\underset{\text{Zinc.}}{\mid} \overline{SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2 \underset{\substack{\text{Porous}\\ \text{partition.}}}{\mid} SO_4}\ \overline{CuSO_4}\ \overline{CuSO_4}\ \overline{Cu} \underset{\text{Copper.}}{\mid}$$

We see here that for every atom of zinc dissolved one atom of copper is deposited, and for every molecule of sulphuric acid decomposed by the zinc, or for every molecule of cupric sulphate decomposed by the nascent hydrogen, one molecule of sulphuric acid is formed. Theoretically, then, the gross quantity of sulphuric acid should remain constant, zinc sulphate should be continuously increasing, while the sulphate of copper should diminish in precisely the same ratio—that is, one molecule or equivalent of zinc sulphate should be formed for every molecule or equivalent of cupric sulphate that is decomposed. Further, for every 65 parts by weight of zinc dissolved, 63 parts by weight of copper should be deposited.

A weak solution of zinc sulphate is frequently substituted for the sulphuric acid solution. In that case no hydrogen at all is generated, so that polarisation from this cause is altogether impossible. The series of chemical reactions presents the same general features. On joining up, the zinc sulphate attacks the metallic zinc, fresh particles or molecules of the salt are formed, and metallic zinc liberated in place of the hydrogen which is produced when sulphuric acid is employed. The liberated zinc decomposes the copper sulphate, forming more zinc sulphate and liberating the copper. Eventually, copper is deposited on the copper plate, the reactions being set forth in the equation :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\substack{\text{Zinc}\\\text{sulphate.}}}{SO_4Zn} + \underset{\substack{\text{Copper}\\\text{sulphate.}}}{SO_4Cu} = \underset{\substack{\text{Zinc}\\\text{sulphate.}}}{2ZnSO_4} + \underset{\text{Copper.}}{Cu.}$$

[illegible]

The substitution of the zinc sulphate for the acid has also the effect of reducing the wasteful consumption of the zinc. Unless the cell is required for immediate use there is really no need to add even the zinc sulphate to the water, the reason for which will be seen presently.

The chemical changes, however, which are brought about in the Daniell by the propagation of the current, constitute only a portion, and that a by no means large one, of the total amount of chemical change that ensues on fitting up the cell. That very porosity of the unglazed earthenware partition, while it allows the two solutions to come into contact, also permits of their diffusion or gradual mixing. All liquids do not diffuse at a uniform rate, the rate of diffusion varying inversely as the square of their specific gravities. The immediate consequence of this is, that some of the copper sulphate solution passes through into the zinc division, where its copper is displaced by zinc, thereby converting the copper sulphate into zinc sulphate. The copper so displaced is deposited in a black spongy mass upon the surface of the zinc, or is precipitated to the bottom of the cell as battery 'mud.' All this means so much waste, for the zinc is dissolved and the copper sulphate decomposed, without the production of any available current of electricity. The deposit on the zinc plate converts the cell, in a great measure, into one with two copper surfaces.

When the battery is intended only for occasional use, or when the external circuit is of relatively high resistance, it is much preferable to use somewhat denser porous partitions, whereby the diffusion of the solutions is to some extent prevented, or at least hindered. The presence of denser porous partitions implies, of course, a proportional increase in the internal resistance of the battery. It may here be mentioned that white unglazed porcelain is harder and less porous than the red variety, and is therefore generally to be preferred.

Great care must also be taken that the various constituents of the cell are of the purest possible character, and all metallic joints must be electrically continuous. A small percentage of impurity in either of the solutions will have most deleterious effects. Three substances are required as pure as our knowledge can render them. The copper sulphate must, above all things, be pure, because of the weakness of the chemical affinity between sulphuric acid and copper. In the event of the salt not being so, the impurities will precipitate the copper and then small 'local actions' will be called into existence, much to the prejudice of the primary or main current. The impurity most common in copper sulphate is iron, which may be readily detected, for, as liquids are essentially diffusive, a small test-tube full will give the same quantitative as well as qualitative result, as any larger quantity. Acid solutions of copper are of a brilliant green hue, while the corresponding ammoniacal solutions, due to the free addition of ammonia solution, are deep blue in colour. If, therefore, we add an excess of ammonia to the acid solution (*i.e.* more than sufficient to neutralise the acid), the copper will be readily retained in the solution, but with the change of colour mentioned above. Iron, however, while it is soluble in acid, is precipitated by ammonia—that is to say, the ammonia will not allow the iron to remain in solution. Should there, therefore, be any iron in the acid solution, it will be precipitated as a dark powder on the addition of the alkaline ammonia. The sulphuric acid or sulphate of zinc, when used, must likewise be free from impurities, the chief of which is again iron. This metal in sulphuric acid gives it a yellowish tinge, even when in small quantities. Good acid should be as colourless as pure water, and when poured from one vessel to another should, if of the requisite strength and specific gravity, have the viscidity of oil. The porous partition, unless carefully made, is liable to contain small particles of cinder, &c., and these tend to decompose the cupric sulphate with a precipitation of the copper, which forms itself into nuggets in the pores of the earthenware and frequently chip or even completely fracture it.

The zinc should be pure, or as nearly so as it can be obtained. Chemically pure zinc, however, is manufactured with great difficulty, and is consequently very expensive. The presence of foreign matter is, nevertheless, a very great deterrent to the good working of the cell, for it must be remembered that the presence in a solution of two metals in contact or otherwise electrically connected, always results in the production of electrical currents. If, therefore, there are particles of foreign metals mixed up with the zinc, there necessarily occurs local currents which act disadvantageously in at least two ways—first by wasting the zinc, and secondly by weakening the main current. As zinc is positive to every available substance (the only metals positive to it being potassium and sodium, which, on account of their extreme affinity for water, are never employed for battery purposes), the admixture of particles, say, of iron, tin, or arsenic, causes small currents to travel from the zinc to these particles, and while the impurities remain to a great extent unaffected (because of their being the negative element), the zinc is constantly suffering a loss by consumption or conversion into a salt. These minute currents are furthermore produced on the surface of the zinc, and must, as already mentioned, interfere considerably with the production of the primary current. The difficulties arising from the presence of impurities are also increased if the zinc is imperfectly or improperly manufactured. The molecular arrangement (or the relative position of the molecules) must be homogeneous throughout the surfaces of each plate, otherwise currents will be set up between the softer and harder parts of the zinc—in a word, they possess opposite electrical properties, so that even if chemically pure zinc were procured, it would not follow as a matter of course that we should be secured against this source of wasteful local action. Concentrated sulphuric acid has, it may be mentioned, no effect on pure zinc provided it is properly annealed—that is to say, that the surfaces have been softened and made molecularly homogeneous. The acid can, therefore, furnish us with a tolerably reliable test for the degree of purity and equable texture possessed by the metal. So important, indeed, is this question of uniformity that a difference of temperature will frequently determine a difference of potential, and therefore cause a current to flow.

The effect both of the presence of any impurity and of unequal hardness can, however, be effectually overcome, at least for a time, by the process known as 'amalgamation.' This process consists in first thoroughly cleansing the surfaces of the metal by immersing it for a time in a dilute sulphuric or hydrochloric acid solution, and subsequently (but while still wet with the acid) coating the surfaces with mercury. This operation is generally recommended to be performed by rubbing the mercury on with a sponge or piece of cloth at the end of a stick ; but this is a very irksome and tedious operation, more especially when the zincs are cylindrical, and it is quite as, if not more, efficacious to pour the mercury (which should afterwards be used for no other purpose) into a flat vessel and lay or roll the zincs in it. This may be thought a wasteful process, but the superabundant mercury can be easily removed by wiping the surfaces over and th standing them on a dish, to allow any mercury that may be s free to fall off. This method is much to be preferred when it required to amalgamate a large number of plates. A very little me cury deposited at the bottom of the zinc division in the batte will suffice to keep the plate well amalgamated for a long time.

By adopting the process of amalgamation the commonest zinc can be rendered thoroughly serviceable for a greater or less period according to the degree of effectiveness with which the process has been carried out. As to its rationale, it appears evident that the function of the mercury is to homogenise the molecular arrangement by uniformly softening the zinc and forming with it a regular amalgam unassailable by pure sulphuric acid. The amalgam in an almost liquid state glides over and covers up any impure particles that have not been dissolved off by the washing process ; as the zinc wears away these particles fall out and drop to the bottom of the cell to do no further harm.

The mercury does not enter into action with the acid or in any other way interfere with the efficient working of the cell, but on joining up the battery the acid attacks and dissolves the zinc more or less uniformly, the mercury eating its way inwards as the superficial zinc particles enter into the solution.

The circular form of battery is very extravagant in the matter f shelf or floor space, while the square or flat types, which have ractically superseded the circular ones, are essentially compact, nd are for that reason to be preferred. The square type was riginally introduced by Dr. Muirhead. It consists generally of a wooden box or trough, into which five double or ten single cells of white glazed porcelain or ebonite are placed, when it presents a neat and compact appearance, as shown in fig. 19. Fig. 20 is a section of one of the single-cell porcelain vessels, fig. 21 illustrating the double-cell form. The latter is square and is very convenient. There is a little ridge along the bottom of each cell (see fig. 20) to keep the flat porous vessel in position. This porous vessel containing the copper plate is filled up with copper

FIG. 19.

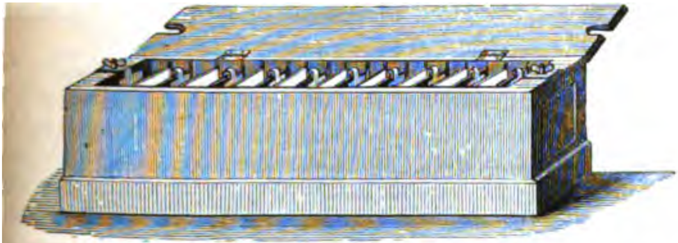


FIG. 20.

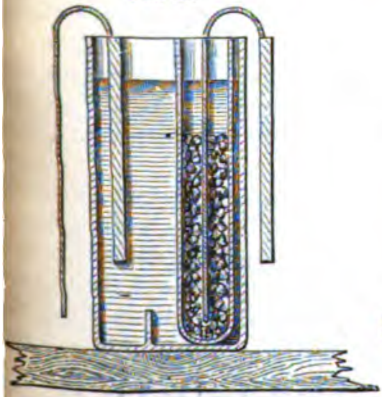
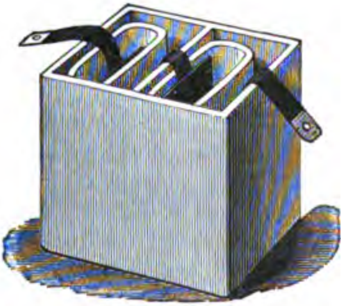


FIG. 21.



sulphate crystals, the zinc, which should be not less than $\frac{1}{4}$ inch thick (to allow for waste by local action), being suspended in the zinc sulphate solution. It will be noticed that the copper plate is attached to the zinc of the next adjacent cell. It is usual in practice to rivet one end of a copper strap on to the copper plate, the zinc being cast on to the other end of the strap. In this way expensive binding screws or terminals are dispensed with, and a good and substantial contact is ensured. The last zinc and the last copper are connected to brass terminals, which become respectively the negative and positive poles of the battery.

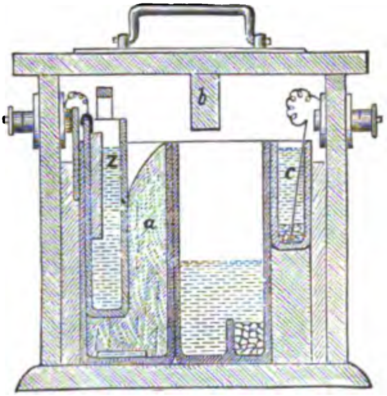
Nothing but clean water (hard water should, if possible, be avoided) is poured into the zinc division, but sufficient is added to bring it up to within about a quarter of an inch of the top of the zinc plate. The battery at the end of about twenty-four hours will be found to be in working order, the sulphate having dissolved in the copper division and enough passed through the poro partition to start the chemical action. Under these circumstances then, a portion of the cupric sulphate that would otherwise b wasted is utilised to convert the water into a solution of zi sulphate. If the battery is wanted for immediate use, the zinc ce must be filled with a weak solution of sulphate of zinc (or sulphu acid), and the copper cell with a saturated solution of sulphate o copper; action then commences at once. It is often more convenient to dispense with the trough or box and place the cells side by side on a shelf. The advantage of this in an extensive battery room is apparent.

All porous pots should be dipped, top and bottom, in melted paraffin wax, so as by filling up the pores to prevent the solutions mingling too freely or rising to the top above the level of the liquids, and so allowing the water to evaporate and the salts to crystallise out. One side of the flat porous pots may also be paraffined with advantage—viz. the side which is remote from the zinc.

A porous pot which has been once used should not be allowed to get dry, as the crystals which form on drying chip it, and will soon render it useless.

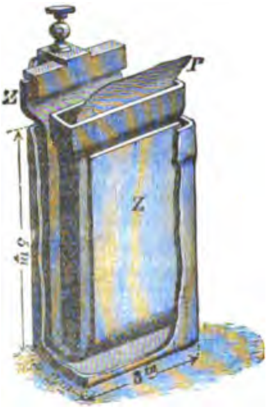
The Daniell cell, when in good condition, can be employed as a standard of electro-motive force, and owing to the ease with which the copper salt is decomposed, the cell possesses one great advantage over the Clark standard cell, in that it does not polarise when joined on short circuit, even when it is giving a more or less continuous current. It has, however, the disadvantage that for accurate measurement it requires a certain amount of attention which must be particularly directed to the zinc division, to keep it free from copper. A very handy and convenient form of Standard Daniell is that shown in fig. 22. In a square wooden box, provided with two terminals for connection, are three watertight chambers. When the cell is not in use, the copper plate *c* is removed to the right-hand chamber containing copper sulphate solution, the zinc plate *z* and the porous pot containing it being transferred to the left-hand chamber. This porous pot is supplied with a semi-saturated solution of zinc sulphate, the copper sulphate solution and its reserve of crystals being placed in the middle chamber. All that is then necessary to place the cell in working order is to remove the copper and the porous pot into the centre division. The stud *b* attached to the lid, prevents it being shut down unless the porous pot has been removed to the outer chamber. Such a cell will maintain an electro-motive force of 1·07 to 1·079 volts for a considerable time, providing that the copper and porous pot are removed to their respective idle chambers, between the tests.

Fig. 22.



We have seen that Daniell absorbed the freed hydrogen by causing it to reduce a metallic salt: Grove and Bunsen in their batteries oxidised the liberated hydrogen by means of an acid, water being produced by this hydrogen instead of sulphuric acid, as in the Daniell. In the negative division concentrated nitric acid is used, into which Grove dipped platinum foil, while Bunsen adopted gas-carbon. Zinc, as usual, constituted the positive plate in each case, the liquid placed with it being a solution of sulphuric acid. The diagram (fig. 23) shows the construction of the Grove. It is usually contained in a flat rectangular glass, porcelain, or ebonite vessel, porcelain being perhaps the best. The amalgamated zinc plate, z, is bent into a U-shape, and supports the flat porous pot which contains the platinum foil, P. By this arrangement each surface of the platinum has opposed to it a surface of zinc, the internal resistance being consequently very low. A strong solution of sulphuric acid (about 1 of acid to 7 or 8 of water) is poured into the outer cell and strong nitric acid having a specific gravity of 1·420 is placed in the inner cell with the platinum. The copper or brass connections or terminals should be lacquered except upon those surfaces which take part in the electrical circuit, to protect them as much as possible from the gases which are evolved during the working of the cell.

FIG. 23.



The action is in the first stage similar to that in the Daniell but there is some diversity of opinion as to what actually transpires in the platinum division. Zinc sulphate is formed by the action of the sulphuric acid on the zinc, and the hydrogen which is thereby released reduces the nitric acid (HNO_3) to water and nitric peroxide (N_2O_4), which ascends as a gas into the air. This gas is distinguishable from all others by its dense brown appearance and its extremely pungent odour.

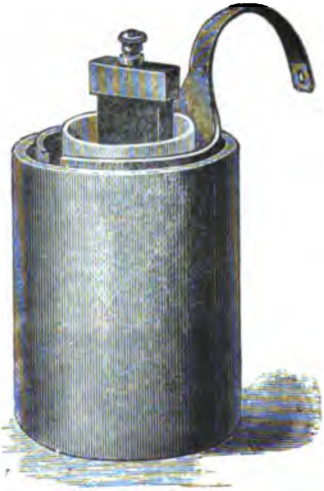
The chemical reactions may be represented by the equation—

$$Zn + SO_4H_2 + 2HNO_3 = ZnSO_4 + 2OH_2 + N_2O_4.$$

It will be noticed that the acid, which, to give the maximum strength of current, should be concentrated, must be seriously weakened as the current is produced. This results, in the first place, from the fact that every atom of hydrogen set free from the sulphuric acid decomposes a portion of the nitric acid, while in the second place the water which is formed dilutes and so weakens the remaining acid. The acid, which, when first poured in, should be quite colourless, is first turned brown by the peroxide, which is more or less soluble in the acid, changing subsequently to green, when it is practically useless.

The Bunsen cell, which is illustrated in fig. 24, is most frequently made in the circular form. The outer jar is of glazed earthenware or glass, and contains a solution of sulphuric acid, ordinarily in the proportion of 1 of acid to 7 or 8 of water, as in the Grove. Into this is placed a cleft zinc cylinder, and inside this is the porous cell, containing a rod of carbon, immersed in strong nitric acid. The porosity of the carbon enables it to present to the liquid a very extended surface, as compared with the platinum of the Grove cell.

FIG. 24.

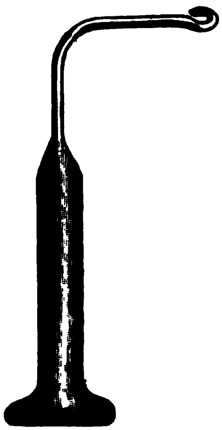


The action in the battery is identically the same as in the Grove, since the carbon and platinum remain chemically unaffected.

The Daniell and the Grove cells are the representatives of two extensive classes of battery. Daniell's has attained its high standard of popularity on account of its cheapness and its constancy. It is much more constant than either of those we have as yet mentioned. The Grove, on the other hand, is very powerful, but, owing to polarisation, it runs down very rapidly, and is not reliable for more than three to four hours at a time. It is, however, important to remember that if the negative plate and its acid are removed from the cell separately and allowed to stand for a time, the acid can be used again and the cell will give a current practically as good as before The same acid can be used three or four times before it is so reduced in strength as to materially affect the current, a state which, as already mentioned, is indicated by the greenish hue imparted to the acid. The chief use o Grove cell in England is for experimental purposes. It has advantage that it is very compact and portable. The Bu has a slightly higher electro-motive force, and it is some cheaper than the Grove. As, however, it is generally constr in the cylindrical form, it is much less convenient.

There are many forms of double-fluid bichromate batt In nearly all of them zinc and carbon are employed for the po and negative elements respectively, the difference being, gen speaking, confined to the depolarising solution surroundin carbon plate. In one of them, however, a great feature is of the means adopted for keeping the zinc well amalgam This cell is known as the 'Fuller,' and it is usually put u round earthenware jar, in which is p a comparatively small porous pot cont a zinc rod of peculiar shape, as shown 25. The zinc is cast on to a stout c wire which passes almost to the bott the rod and helps to keep it intact. T three ounces of mercury are placed porous pot, which, on the addition solution (dilute sulphuric acid), creeps surface of the zinc by the force of ca attraction and so keeps it uniforml automatically amalgamated. A small c plate is placed in the outer vessel in a so of bichromate of potash, derived, how from a stiff paste, of which a quanti placed in the bottom of the cell, and w contains, probably, a quantity of free chromic acid, soda nit &c. An unusually large quantity of this solution is gene provided in order to maintain its strength for a longer period time than would be the case were the more usual proportio adopted. The chemical action is practically the same as that the single-fluid bichromate cell. What is true of the nitric ac cells of Bunsen and Grove is also true, although, perhaps, to a le degree, with each and every form of bichromate of potash or chromic acid cell—viz. that polarisation and the accompanyi

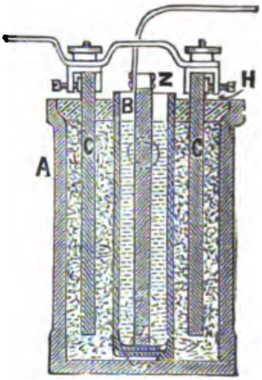
FIG. 25.



reduction in the electro-motive force, and therefore also in the current strength, sets in after the battery has been in use for a few hours more or less. The electro-motive force of the cell is, however, high, ranging from 1·9 to 2·15 volts. Its internal resistance is also very low, whence it finds considerable favour.

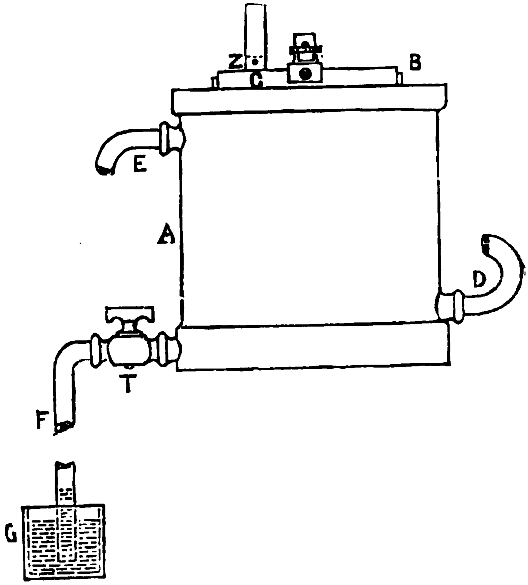
The most ingenious battery yet constructed for electric lighting purposes is probably that of Mr. A. René Upward, the principle of which will be gathered from figs. 26 and 27. The positive plate, Z, is of cast zinc immersed in water (which afterwards becomes zinc chloride), contained in the porous pot, B. The negative element consists of two carbon plates, C C, joined together and placed in the outer vessel, A, of glazed earthenware, the space between A and B being then closely packed with crushed carbon and sealed in with a layer of cement, H. Chlorine gas, which has considerable affinity for zinc, is led into the outer cell by the tube, D (fig. 27), and, passing between the small pieces of carbon, finds its way into the zinc division, where it enters directly into chemical union with the zinc forming zinc chloride, thus $Zn + Cl_2 = ZnCl_2$. Such of the gas as is not retained in the one cell passes through the outlet tube, E, to the bottom of the next cell. As the chloride of zinc solution passes through the porous partition, it accumulates to a very small extent at the bottom of the outer vessel, and thence, on the tap, T, being turned, it flows through the tube, F, into the receiver, G. There is, however, always sufficient water or solution in G to cover the end of the tube F to prevent air passing upwards into the cell. Such a cell, measuring 11½ × 5½ inches and 12½ inches deep, offers an internal resistance of about 0·2 ohm, and furnishes an electro-motive force of 2·1 volts.

FIG. 26.



In a later form each cell contains five cylinders of zinc joined together so as to give a large positive surface, the negative element consisting of eight carbon plates. The other details correspond to those shown in figs. 26 and 27. The inlet tube is connected direct to the apparatus in which the chlorine gas is generated, the outlet tube being connected to the inlet of the next cell, the outlet of which is in its turn connected to the bottom of the first of a series of vertical columns, made by carefully sealing together a number

FIG. 27.



of ordinary earthenware drain-pipes.[1] The top of the first of these columns is connected to the bottom of the second, and so on, the top of the last of the series being provided with an outlet tube extending into the outer air. Chlorine gas is rather more than twice as heavy as air, so that as the gas first enters at the bottom of the cells it drives out the superincumbent air by ordinary displacement. Similarly with the reservoir columns, the first being filled with chlorine before any enters the second column, and so on. The connecting tubes are of lead, which is the most durable material available, as it has only a feeble affinity for chlorine at ordinary temperatures. A piece of glass tubing is let into each of the lead pipes connecting the reservoir columns, and, the back of the glass being painted white, the presence of the chlorine is easily recognised by its distinguishing greenish-yellow hue.

---

[1] In the earlier form of the battery, a very pretty and ingenious aspirator was connected to the battery which served the purpose of drawing the gas through as required.

There are various ways of generating chlorine, the method employed by Mr. Upward being that of heating a mixture of manganic oxide, sulphuric acid, and brine (sodic chloride). The reaction is represented by the equation :—

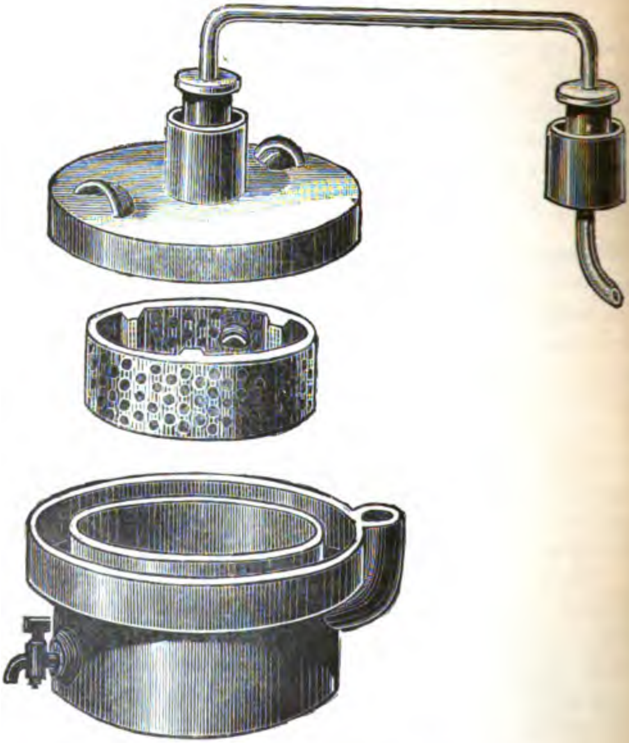
$$\underset{\substack{\text{Manganic}\\\text{oxide.}}}{MnO_2} + \underset{\substack{\text{Sulphuric}\\\text{acid.}}}{2SO_4H_2} + \underset{\substack{\text{Sodic}\\\text{chloride.}}}{2NaCl} = \underset{\substack{\text{Sodic}\\\text{sulphate.}}}{SO_4Na_2} + \underset{\substack{\text{Manganous}\\\text{sulphate.}}}{SO_4Mn} + \underset{\text{Water.}}{2OH_2} + \underset{\text{Chlorine.}}{Cl_2}$$

The whole of the chlorine contained in the salt is thus reduced to the gaseous state.

The apparatus employed for the generation of the gas is illustrated in fig. 28. In a round earthenware pan is placed the perforated earthenware tray previously filled with the black manganic oxide, sufficient for two or three weeks' run. The cover is then placed in position and sealed with water run into the groove shown in the pan. The brine and acid, which are stored in jars, are supplied daily through the inlet tube shown on the right of the pan, the spent liquid being drawn off at the tap on the left, which is connected directly with the drain by means of a sealed pipe. The whole being placed in a sand bath, sufficient heat is supplied by a small gas jet or oil flame to bring about the required chemical changes. The gas is conveyed by the tube shown at the top to the first of the battery cells. When it is required to re-charge the retort with manganic oxide, it is flushed out with water (entering at the same aperture as the acid) to remove any trace of the chlorine gas. The lid and tray of spent oxide are then taken out and a spare tray filled with fresh oxide inserted and the lid replaced.

These cells might be joined up in a sufficiently long series to light a number of incandescent lamps directly, but that number would be limited owing to the comparatively high internal resistance of the battery. It is suggested, therefore, to employ only a couple of cells, and with them to charge, one by one, a number of secondary cells (see Chapter XIV.), the primary current being automatically switched from one cell to the next, after it has been charging it for a certain time. Clever in conception as this battery undoubtedly is, it is scarcely one that could be placed in the hands of inexperienced people, or be relied upon to maintain an electric light installation for any length of time. Chlorine gas, again, is very insidious, and its occasional escape in greater or less quantities could hardly be prevented. Were it perfect, however, there would only be a limited field open for its employment, and that on a very small scale. Its expense would prevent it ever entering

FIG. 28.



into competition with the dynamo machine for work on a large scale.

There are, of course, a vast number of cells which we have not considered it necessary to describe here, but they may generally be placed under one or other of the typical heads, viz. the Daniell with a metallic salt, or the Grove with an acid, in the negative division. The general difference is that the latter polarises more or less rapidly, while the former does not polarise, but is kept constant by the metallic deposit upon the negative plate.

Primary batteries are of but little service in electric lighting. They are, of course, valuable for testing purposes, but as sources of current for the electric light they are altogether out of place, except for small isolated work, owing to the fact that zinc, which is in every case used as the positive plate, and which, being consumed in the generation of the current, corresponds to the coal consumed in an engine, is very many times dearer than coal. Even were expense a question of minor importance, there still remains the fact that primary batteries are very troublesome to maintain, and more often than not give off noxious fumes, which are also as a rule highly corrosive. What is really wanted, putting aside altogether the question of expense, is some simple form of cell, of which the constituents can be easily obtained and replaced; from which no injurious fumes can arise; which shall have a high electro-motive force and a low internal resistance, and be fairly constant withal.

There are three considerations that have to be taken into account when determining what kind and what number of cells it would be most advisable to employ for any particular purpose—viz. the relative constancy and electro-motive force, and the ratio between the internal resistance of the cell and the external resistance, or the resistance of the connecting wires and apparatus. It will have been gathered that there is in this matter of electro-motive force and constancy considerable variation. We will not enter here into the matter of expense, for in the end that which is the best cell for any particular purpose generally proves to be also the cheapest. The internal resistance is, however, an important factor. If it were negligible, it would, for example, be possible to maintain a current of one ampere by one Daniell cell working through an external resistance of one ohm, for as (see Chapter II.)

$$\text{C} = \frac{\text{E}}{\text{R}}, \text{ then } \frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere.}$$

But the average Daniell cell offers four ohms resistance, so that the current, where R is the external resistance of one ohm, and r the internal resistance, would be

$$\frac{\text{E}}{\text{R} + r} = \frac{1}{1 + 4} = \cdot 2 \text{ ampere ;}$$

and if we were to attempt to increase this current materially by the addition of, say, nine other similar cells, we should fail, for then

$$\frac{10\text{E}}{\text{R} + 10r} = \frac{10}{1 + 40} = \cdot 25 \text{ ampere nearly.}$$

Similarly, with 100 such cells through this unit resistance—

$$\frac{100\text{E}}{\text{R} + 100r} = \frac{100}{1 + 400} = \cdot 25 \text{ nearly.}$$

We see, then, that increasing the number of cells in this way when the external resistance is low, produces no correspondingly good effect, for the simple reason that, although we might proportionally increase the electro-motive force by so doing, we should at the same rate increase the circuit resistance. As a matter of fact, no ordinary Daniell cell or battery can possibly develop a current of one ampere, its internal resistance being too high.

On the other hand, were we to employ Grove cells (which for simplicity we will assume to have an electro-motive force of 2 volts per cell), the advantage of increasing the number of cells on a low resistance circuit soon becomes apparent. For example, with an external resistance of 1 ohm and an internal resistance of ·2 ohm per cell, one cell would give us,

$$\frac{\text{E}}{\text{R} + r} = \frac{2}{1 + \cdot 2} = 1 \cdot \dot{6} \text{ amperes.}$$

Two such cells would produce

$$\frac{2\text{E}}{\text{R} + 2r} = \frac{4}{1 + \cdot 4} = 2 \cdot 85 \text{ amperes.}$$

nd three cells

$$\frac{3E}{R + 3r} = \frac{6}{1 + \cdot 6} = 3\cdot 8 \text{ amperes nearly.}$$

imilarly, four cells would give 4·4 amperes and five cells would ield 5·0 amperes. But from ten cells we should only get

$$\frac{10E}{R + 10r} = \frac{20}{1 + 2} = 6\cdot\dot{6} \text{ amperes.}$$

While with 100 such cells the current would be

$$\frac{100E}{R + 100r} = \frac{200}{1 + 20} = 9\cdot 5 \text{ amperes,}$$

howing again that as the internal resistance approaches or exeeds the external, the proportional current from the battery is educed. When, however, the external resistance is relatively igh, say 1,000 ohms, the battery resistance becomes proponally low, and, therefore, to a certain extent, negligible. The urrent from one Daniell cell would be

$$C = \frac{E}{R + r} = \frac{1}{1000 + 4} = \cdot 000996 \text{ ampere.}$$

With ten cells we should get,

$$\frac{10E}{R + 10r} = \frac{10}{1000 + 40} = \cdot 00961 \text{ ampere,}$$

r, practically, a current of tenfold strength.

Similarly, with a battery of 100 cells, we should get

$$\frac{100E}{R + 100r} = \frac{100}{1000 + 400} = \cdot 0714 \text{ ampere.}$$

Again, one Grove cell would give through 1000 ohms

$$C = \frac{E}{R + r} = \frac{2}{1000 + \cdot 2} = \cdot 002 \text{ ampere,}$$

and ten cells would give

$$\frac{10E}{R + 10r} = \frac{20}{1000 + 2} = \cdot 0199 \text{ ampere.}$$

From 100 cells we should get—

$$\frac{100\text{E}}{\text{R} + 100r} = \frac{200}{1000 + 20} = \cdot 196 \text{ ampere.}$$

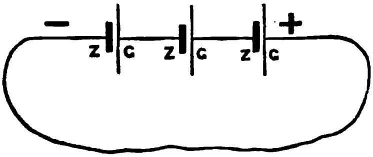
With either the Daniell or the Grove the strength of the current increases in almost the same ratio as the number of cells when the external resistance is high. But as the Grove is vastly inferior to the Daniell in constancy, and as it is a very expensive form of battery, the deduction is that Daniell cells should be used for circuits of high resistance, compensating for their lower electromotive force by a corresponding increase in numbers. On the other hand, the Grove, in consequence of its low internal resistance, is better adapted for circuits of low resistance.

The internal resistance, however, of different cells of any particular type varies inversely as the size of the plates (counting only the active or opposed surfaces). It also varies directly as the distance between them (making due allowance for the resistance of the porous pot, which would, of course, have a constant value unless varied in size or thickness). The meaning of this is plain, for if we were to double the size of the plates we should halve the resistance and proportionally increase the current strength.

The same object is attained by joining cells in 'parallel.' So far we have only considered them as joined in series, that is to say, the copper of one cell joined to the zinc of the next and so on. Under such circumstances the electro-motive force of the battery is equal to the sum of the electro-motive forces of the various cells. If the coppers of two cells are joined together, and likewise the zincs, and the two junction wires connected to the external circuit, a current will be developed by an electro-motive force equal to that of one cell, the joint resistance of the two equal cells being half that of one of them used separately. The arrangement is, in fact, equivalent to doubling the size of the plates.

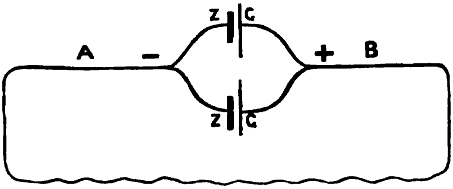
This will, perhaps, be made clearer by a reference to the diagrams, figs. 29, 30, and 31. Fig. 29 represents a battery of three cells joined in series, the short thick strokes representing the zinc or positive plates, and the long thin ones the copper or negative plates. Fig. 30 shows two cells joined up in parallel. If they are both of exactly the same electro-motive force, no current can ow from C to C or from *z* to *z*, but on joining the external wires and B together, a current would be generated by each cell and

FIG. 29.



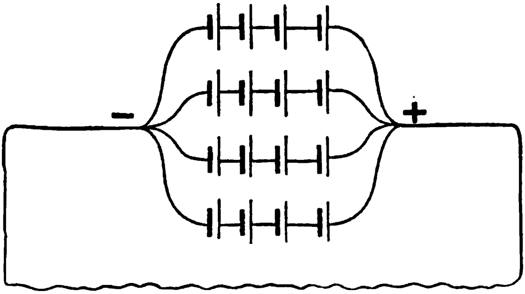
pass through the external circuit from B to A. As already stated, the joint resistance of these two cells would be half that of one

FIG. 30.



of them. With a low external resistance the current strength would be increased proportionally. In fig. 31 are shown sixteen

FIG. 31.



cells divided into four sets of four cells each, the sets being joined up in parallel. On completing the external circuit a current will flow, having an electro-motive force equal to that of four cells, but the battery resistance will be only one-fourth of that of fo cells.

The joint resistance of any number of parallel batteries i equal to $\frac{rs}{\text{B}}$, where r is the resistance per cell, s the number o such cells joined up in series in each individual battery, and B the number of such batteries joined together in parallel. This i simply an application of the law that with a number of conducto N, of uniform resistance, R, joined together in parallel, their joi resistance is equal to $\frac{\text{R}}{\text{N}}$. For rs is the total resistance of eac of the batteries joined together in parallel. This arrangeme is sometimes very advantageous; for example, if sixteen Danie cells, each of 1 volt electro-motive force and 4 ohms intern resistance, are employed in series for a circuit of 4 ohms extern resistance, the current will be

$$\frac{16}{4 + 64} = {\cdot}235 \text{ ampere} \quad . \quad . \quad . \qquad (1).$$

By dividing the cells into two sets of eight cells each and joinin these in parallel, the current is increased, thus

$$\frac{8}{4 + 16} = {\cdot}400 \text{ ampere} \quad . \quad . \quad . \qquad (2).$$

On rearranging the cells, as shown in fig. 31, the current become

$$\frac{4}{4 + 4} = {\cdot}500 \text{ ampere} \quad . \quad . \quad . \qquad (3).$$

Pursuing this plan any further, however, results in a diminution o the current; for example, if eight sets of two cells each are joined in parallel, we get

$$\frac{2}{4 + 1} = {\cdot}400 \text{ ampere} \quad . \quad . \quad . \qquad (4).$$

While with the whole of the sixteen cells joined in parallel we get only

$$\frac{1}{4 + {\cdot}25} = {\cdot}235 \text{ ampere} \quad . \quad . \quad . \qquad (5).$$

With circuits of comparatively low external resistance there is therefore, a best possible arrangement of the cells to give the trongest possible current, and with any given number of cells his arrangement is arrived at when the internal resistance is equa o the external, or when $R = \frac{rs}{B}$.

Such an arrangement is not, however, economical; nor, indeed, s any arrangement, unless the external resistance is considerably in excess of the internal. As has been already stated, the strength of the current is the same in all parts of the circuit, consequently in (1) sixteen times as much zinc, &c., is consumed in the sixteen cells as would be consumed in a single cell capable of maintaining an equal current. In (3), however, each set of four cells must be considered as a separate or branch circuit, and only one-fourth of the current flowing in the external circuit would flow through each of these separate sets. The external current is approximately wice as strong as in (1). Therefore the individual current in each ell and the consequent consumption of zinc is only half as great. n (5), where there are sixteen cells in parallel, a current is produced equal to that resulting from a battery of sixteen cells in eries, but, the cells being joined up in parallel, only one-sixteenth f this current flows through each cell, so that the total consumption of zinc in the sixteen cells is equal to that in but a single cell n (1), clearly demonstrating the advantage, from an economical point of view, of using batteries much lower in resistance than the wire or apparatus through which the current has to flow.

One important feature concerning the proportion between the gross electro-motive force of the battery and the difference of potential it can maintain in any given external circuit requires careful consideration, for it is a feature that is frequently lost sight of. It was pointed out in Chapter II. that in any given circuit the fall of potential varies directly as the resistance, so that in (1), where the internal bears to the external resistance the proportion of 16 to 1, only one-seventeenth of the 16 volts developed by the battery is available in the external circuit, the remaining sixteen-seventeenths being absorbed in overcoming the resistance of the battery. In (3) the resistances outside the battery being equal to that inside, the electro-motive force of 4 volts developed is halved, 2 volts being available for the external circuit. Similarly in (5), the available electro-motive force for the external circuit is sixteen-seventeenths of a volt (the gross electro-motive force developed being 1 volt), or equal to that produced by the sixteen cells joined up in series, as in (1), where, as already shown, the consumption of materials is sixteen times as great, and, speaking generally, we may say that

$$P = E \frac{R}{R + r}.$$

Where E is the electro-motive force developed by the battery, R is the external resistance, r is the internal resistance, and P the available potential difference at the terminals of the battery. For example, with a battery, as in (4), whose internal resistance is 1 ohm working through an external resistance of 4 ohms, and having an electro-motive force of 2 volts, the available potential difference will be

$$P = 2 \frac{4}{4 + 1} = 1 \cdot 6 \text{ volts.}$$

The available potential difference can also be ascertained in another way which does not involve the necessity for ascertaining the external resistance. Ohm's law declares $C = \frac{E}{R}$ or, $E = CR$. And this is true either of a complete circuit or simply of a part of a circuit. If, for instance, in a circuit of known or unknown resistance the current strength is found to be, say, 1·5 amperes, and that a portion of the circuit offers a resistance of 3 ohms, then the fall of potential, or the electro-motive force absorbed, in that portion of the circuit will be

$$E = CR = 1 \cdot 5 \times 3 = 4 \cdot 5 \text{ volts.}$$

If the known resistance is that of the battery (r), it follows that 4·5 volts will be the electro-motive force absorbed by the battery, and if that is deducted from the total electro-motive force developed (say, 20 volts), the remainder will be the available potential difference for the external circuit, or

$$P = E - Cr = 20 - (1 \cdot 5 \times 3) = 15 \cdot 5 \text{ volts.}$$

Occasion sometimes arises for substituting one form of battery for another without making any appreciable change in the current strength. If the internal resistance were negligible, this would, of course, be a matter of no difficulty ; but even when it is requisite to make allowance for the battery resistance, a simple formula can be employed to ascertain the number of cells necessary to develop a given current strength. For example, suppose that a battery of 100 cells, with an electro-motive force of 1 volt and an internal resistance of 4 ohms per cell, sends a current through an external resistance of 400 ohms, then the current will be

$$\frac{100E}{100r + R} = \frac{100}{400 + 400} = \cdot 125 \text{ ampere.}$$

Substituting some other form of battery with an electro-motive force of 2 volts and an internal resistance of 1 ohm, and letting n be the number of such cells necessary to develop 0·125 ampere, then

$$\frac{n2}{n \times 1 + 400} = \cdot 125 = \frac{1}{8} \text{ ampere,}$$

that is to say,

$$\frac{2n}{n + 400} = \frac{1}{8},$$

or,

$$16n = n + 400$$
$$15n = 400$$
$$n = \frac{400}{15} = 26\cdot\dot{6}.$$

Twenty-seven of these 2-volt cells would maintain in the circuit a current of

$$\frac{27E}{27r + 400} = \frac{54}{27 + 400} = \cdot 126 \text{ ampere.}$$

Twenty-six cells would be insufficient for the purpose. This formula also possesses the advantage of providing the same potential difference at the terminals of the battery, as well as that of furnishing the number of cells necessary to develop an equally strong current.

CHAPTER IV.

MEASUREMENT OF CURRENT STRENGTH.

HAVING in the preceding chapters shown how a current of tricity can be generated and maintained, and having also expl the various units by which we can measure that current, as we the resistance, and the pressure or electro-motive force w maintains the current, it behoves us now to turn our attentio the methods of making such measurements and the consider of the laws involved. In order to make the student's pro at this difficult stage as easy as possible, we will approach subject experimentally.

If a wire, A B (fig. 32), carrying a current is brought another wire, C D, also carrying a current, it is found that th a decided action between the two wires. If the currents flowing in the same direction, as shown by the arrow-hea fig. 32, the wires are attracted one to the other. On the o hand, if the currents travel in opposite directions, as in fig. 3 repulsion ensues.

FIG. 32.

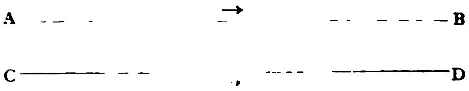
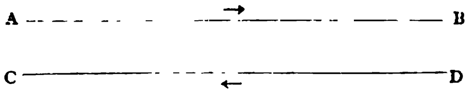


FIG. 33.



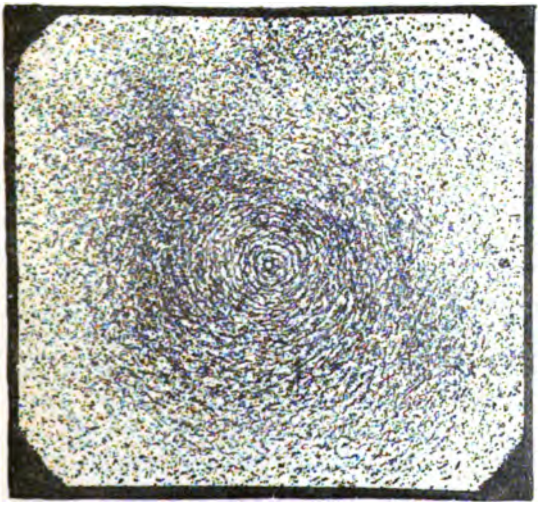
The force of this attraction or repulsion depends, among othe considerations, upon the strength of the current. It would b ssible, therefore, to take advantage of this effect as affording a eans of estimating or measuring current strength, and a device r so doing will be described presently.

Now it is impossible for any action to take place between the ro wires without the aid of some intervening medium to transmit ie force. This medium is the same as that which transmits the ectrical stresses in the other or static state of electricity, that state which a body affected by it is said to be electrified or charged ith electricity, and is, in all probability, the light-carrying her.

Although it is difficult to understand the precise action in this se, it is easy to show experimentally the direction in which the rce acts.

If we thread a wire which is carrying a current through a piece cardboard, and sprinkle iron filings on the cardboard, they will rrange themselves in concentric circles round the wire as shown n fig. 34. This arrangement is caused solely by the current nd may be observed at any part of the wire. The lines thus

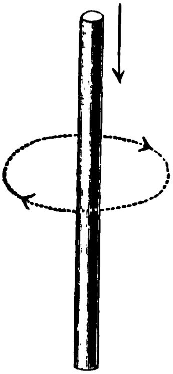
FIG. 34.



marked out, which show the direction in which the force due to the current acts, are called 'lines of force.'

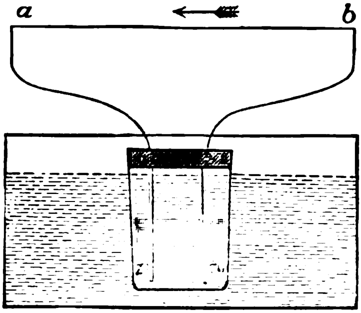
As in the case of the imaginary lines considered in Chapter I., it is necessary to assume for them a certain direction. That direction along a line of force, indicated by the arrows in fig. 35, is called the 'positive' direction. The direction can be impressed upon the memory by thinking of the act of using a corkscrew. If the longitudinal direction of the screw, either *into* or *out of* the cork, be taken to represent the direction of the current, then the positive direction of the lines of force will be that in which the handle rotates, so that if in fig. 35 the downward direction of the current were reversed, the positive direction of the lines of force would be in the opposite direction to that indicated by the arrow-heads. The space around the wire in which the effect of the current is perceptible is called an 'electro-magnetic field,' and it is important to remember that the strength of this field is exactly proportional to the strength of the current producing it. It extends from the axis of the wire as a centre throughout the surrounding space, but as the distance from the wire increases, the effect is weakened until it at last becomes so feeble as to be imperceptible. The lines of force traversing this field obey precisely the same laws as those laid down for the lines due to a static charge, and the interaction between two sets of lines of force can always be predicted by remembering that their universal tendency is to coincide in direction and to shorten themselves.

FIG. 35.



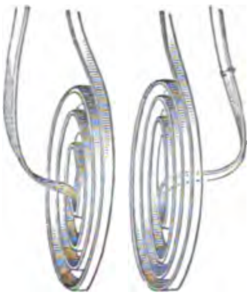
Reverting to the experiment with the two wires carrying the currents, it may be said that the force exerted between them always tends to move them so that they shall take up such a position that the currents flow in the same common direction (as in fig. 32) and that the wires as nearly as possible coincide. To prove this, it is necessary to allow at least one of the wires to be capable of moving freely and with as little restraint or friction as possible. This can be done by means of a simple device for constructing a movable or floating battery cell. Let a cork be fitted to a small glass beaker partly filled with diluted sulphuric acid, and through the cork pass wires carrying thin strips of zinc and copper or silver, completing the circuit externally by means of a stiff but not too heavy piece of wire, as shown in fig. 36. The small beaker cell can then be placed in a larger beaker, or any other convenient vessel full of water, and, unless too much acid solution has been placed in the smaller beaker or the solid portions are made unnecessarily heavy, the cell will float readily upon the water. If a wire carrying a strong current is placed parallel to the straight part of the wire, *a b*, so that the currents flow in opposite directions, the wire *a b* will be repelled, and, the cell floating away, will turn completely round, so that the currents flow in the same direction ; it will then be attracted until *a b* lies as near as possible to the other wire.

FIG. 36.



These effects may be increased by increasing the length of the wires, but very long straight wires would be cumbersome and, in fact, impracticable. It is, therefore, more convenient to coil them up into flat spirals (fig. 37), covering the wire with silk, cotton, or some insulating material, to prevent adjacent convolutions getting into contact. The effect between the spirals will be identically similar to that between the same two wires straightened out. For many purposes, however, it is preferable to coil the wire into a long spiral or helix. In fig. 38 one of the helices, A B, is floated in a manner similar to that adopted in fig. 36, the other helix, *a b*, being placed near it. The action between two such helices is very decided, and, being of exactly the same character as that between the straight wires

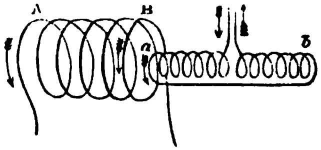
FIG. 37.



or flat spirals, may be predicted by remembering the laws we have just stated.

If the currents are flowing in opposite directions round adjacent ends of the spirals or helices, repulsion will take place, and the floating helix, moving more easily than the other, will recede, and, turning completely round on its vertical axis, will approach with its opposite end to the fixed spiral, as in fig. 38. The currents will then be flowing in the same direction, and the floating helix being comparatively large and its movements not restricted, it will not come to rest until it has threaded itself on to or over the other spiral. Such a spiral or helix of wire acts as if the force resided at its extremities, which are termed its 'poles,' and it is for this reason that this form of spiral is called a solenoid.

FIG. 38.

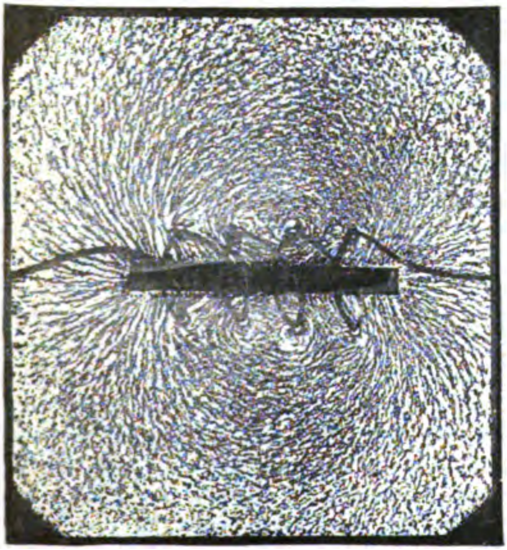


Now the strength of an electro-magnetic field may be measured by the density of its lines of force or the number contained in a given area. From the experiment shown in fig. 34, it is clear that the lines are much denser near the wire than at a distance from it. This is also the case when the wire is coiled up into a helix. The greater part of them there form little circles, closely embracing the wire from which they are generated, and comparatively few of these circles of force pass through the space at the ends or poles of the solenoid, where the force, generally speaking, appears to be concentrated. It will be evident that if we can by any means divert the circles of force so as to compel more of them to pass through the ends of the solenoid, then its effective strength will be greatly increased.

Experiment has demonstrated that iron offers a far easier path for these lines of force than the air does—so much easier, in fact, that they will alter their circular shape and extend a considerable distance from their respective portions of the wire in order to pass hrough a piece of iron. This affords us a ready means of leading he lines to, and concentrating them at almost any point we please. It may be mentioned that the relative facility with which the lines of force are propagated by good soft iron, or the electromagnetic conductivity of the iron as compared with that of air, may be as high as 20,000 to 1.

If, then, we place a bar of iron inside a solenoid, a large percentage of the lines of force lose their circular form, and, passing through this iron ‘core (as it is called), they leave it at its ends to complete their excursion round the wire from which they were generated. An example of this action of iron is shown in fig. 39,[1] which illustrates the field developed by a powerful current travelling through a solenoid of a few turns, having a core of compara-

FIG. 39.



---

[1] We are indebted to the proprietors of *Engineering* for permission to reproduce figs. 39 to 42.

tively small dimensions. Were a larger or more massive core to be introduced, even more of the lines of force would extend themselves through the iron instead of circulating in the immediate vicinity of the wire.

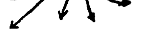
Fitted with these iron cores, the strength of the action between two solenoids is enormously increased. But here we must issue a word of warning. It must not be supposed that because we thus increase the polar strength of the solenoid, we have even in the slightest degree augmented the electro-magnetic force itself. With a given current and a given length of wire, that force is a constant quantity, the sum total of which cannot, in any sense of the word, be increased by the addition of a mass of iron, or even by any variation in the disposition of the wire, whether we wind it into a spiral, a solenoid, or use any other device. Were we able to augment the total force by any of these means, there would be an end to the law of the conservation of energy, which, as has already been pointed out, declares that when any one force is produced or developed it can only be at the expense of an equal amount of energy previously existing in another or a similar form. Force is indestructible; neither can we create it. The doctrine, therefore, so frequently laid down that the introduction of an iron core increases the electro-magnetic strength of a coil of wire, is misleading. The only means of increasing that strength or force is by increasing the current, or, what amounts to the same thing, by increasing the length of wire and increasing the battery power in sufficient proportion to maintain the same current strength. Let us state positively, even at the expense of a little reiteration, that what we really do, by the introduction of the iron core, is to concentrate a much larger proportion of the available force at those points where it acts at the greatest advantage, namely, at the poles of the solenoid. We would impress upon the student the necessity for ever keeping these facts clearly in mind.

The amount of attraction or repulsion exhibited by the solenoids furnished with their iron cores might be used as a means of measuring current strength, but the arrangement is not a convenient one, owing chiefly to the difficulty in obtaining perfect freedom of motion, the liability of variation in the current strength, and the varying properties of the iron.

Were it not for these disadvantages we could keep the electro-magnetic force of one of the solenoids constant, and send the currents to be compared and measured through the other. But here Nature comes in to aid us, for it is found that if a piece of *hard* iron or steel is used as a core for the solenoid, it retains more or less permanently a large portion of the electro-magnetic properties originally produced by the current. The power or ability of retaining such effects or properties is known as the 'retentivity' of the iron or steel, and depends entirely upon its chemical composition and mechanical or molecular structure. This retentivity is the same property as that hitherto known as 'coercive force,' which was certainly a misnomer and a libel upon the metal. If retentivity corresponds to anything at all, it is to *inertia* rather than to anything that can fairly be described as coercive. The similarity to mechanical inertia is seen in the fact that those samples which transmit the lines of force freely, retain scarcely any of the influences producible by them, while, on the other hand, hard iron and steel, which resist the propagation of the lines of force, resist equally well the vanishing of these lines after the cessation of the current which called them into existence.

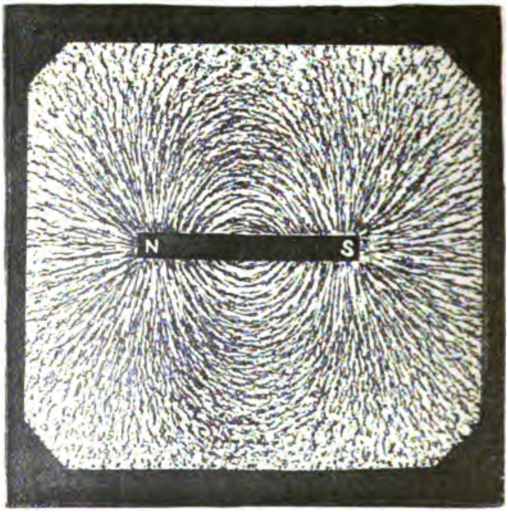
A piece of iron or steel which acquires and so retains the power of acting as a solenoid, is called a permanent magnet, or simply a magnet, and its extremities are also called poles. The lines of force still enter and leave the steel as they did before it was removed from the helix, the direction being shown in fig. 40. The end, S, at which they enter is called the south-seeking pole of the magnet, and the other its north-seeking pole.

FIG. 40.



The actual arrangement imparted to iron filings sprinkled on a sheet of paper placed over a permanent steel magnet is beautifully illustrated in fig. 41. Such a distribution of the filings would take place in any plane parallel to the axis of the magnet, for the lines of force radiate from the poles similarly in all directions. The

FIG. 41.



distribution observed when the paper is placed on the end of the magnet and at right angles to its axis is shown in fig. 42.

If we know the direction in which the current passes round a piece of iron or steel, it is easy to predict the direction of its polarity; for if we look at the end of the bar and the current is then flowing round it in a right-handed direction, as in fig. 43, that end will be a south-seeking pole; but if the current flow in a left-handed direction, as in fig. 44, that end will be a north-seeking pole.

It is the practice to enter into a detailed description of the difference between right- and left-handed helices with a view to facilitating a recollection of the electro-magnetic polarity. Thus a left-handed helix (fig. 45) is one in which, from whichever end the current enters, it will travel in the opposite direction to that taken by the hands of a clock, and will develop north-seeking polarity at the end at which it enters and south-seeking polarity

FIG. 42.

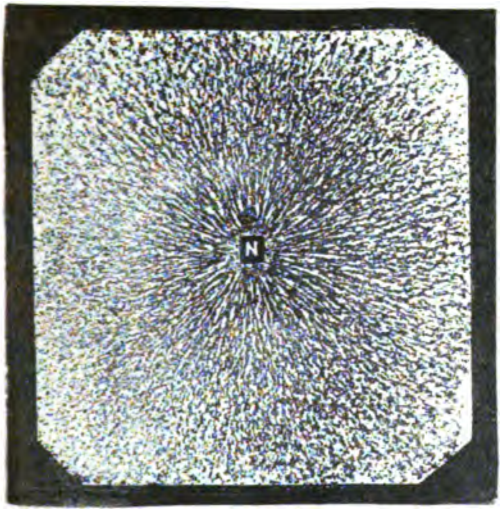


FIG. 43.

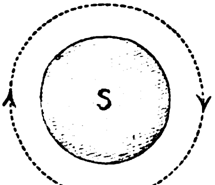


FIG. 44.

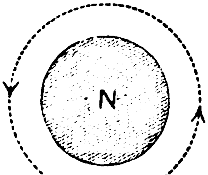
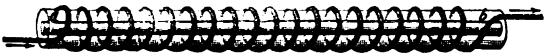
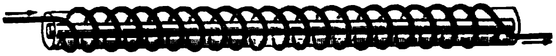


FIG. 45.



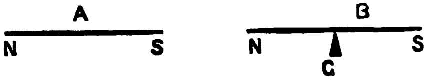
at the end of emergence. Conversely, a right-handed helix (fig. 46) is one in which the current will travel round in the same direction as the clock-hands. In this, the entering end becomes a south pole and the other a north pole. But all this is superfluous. It is sufficient to regard the cause and effect in the way indicated in the preceding paragraph.

FIG. 46.



It is noteworthy that two magnets act one upon the other in precisely the same manner as two helices or a helix and a magnet, for in every case the movement or motion imparted is such as will tend to make the lines of force coincide. Thus, if one magnet, A (fig. 47), is brought near another, B, which is suspended

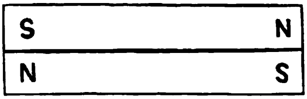
FIG. 47.



by a thread or pivoted on a needle-point at C, so that it can tu freely about its centre, the force exerted between them will e deavour to make the suspended needle take up such a positi as to allow the lines of force due to both magnets to pass throu them in the same direction. This will happen when the magne are in line and when their opposite poles are adjacent, as shown fig. 47. In other words, there will be repulsion between simil magnetic poles and attraction between dissimilar ones.

If, however, both magnets are allowed perfect freedom motion, their ultimate position will be that shown in fig. 48, th

FIG. 48.



magnets then lying side by side with their dissimilar poles adjacent. In this position the coincidence of the lines of force is at a maxi mum, that is, the lines due to each magnet turn round at the en and pass through the other, and in so doing assume the easiest path for their completion. If pieces of soft iron, called armatures or keepers, were placed across the extremities of the magnets, the circuit of the lines of force would be continued through them to such an extent that few or none of the lines would traverse the air. These armatures are, however, rarely made properly, their mass being far too small, and their shape far from the best possible; but this point we will deal with more fully in Chapter VII.

The strength of a magnet pole can be estimated by measuring the force with which it attracts or repels another pole, the force being equal to the product of the two polar strengths; or, if M represents the strength of one pole, and M_1 the strength of the other, similarly magnetised, the force of their repulsion will be $M \times M_1$. This force of repulsion is not, however, the same at all distances, but varies inversely as the square of the distance, so that we might express the force f, between two magnet poles, by the simple formula,

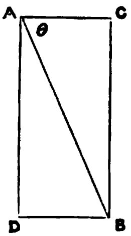
$$f = \frac{M \times M_1}{d^2},$$

where d equals the distance in centimetres between the poles. It is important to bear in mind that the distance between the two poles of each magnet should be as great as possible—or, in other words, that the magnet should be as long as possible—to minimise the error that would be produced by the ever-present tendency of the remote poles to act contrariwise to the adjacent ones.

We have already defined the dyne as the unit of force, and the magnet pole of unit strength is such a one that if placed at a distance of one centimetre from a similar and equal pole, it will repel it with a force of one dyne. Consequently, the strength at any point in any field can be determined by measuring, in dynes, the repulsion at that point of a magnet pole of unit strength. In every case, then, the force acting upon a magnet pole is found by multiplying the strength of the pole by the strength or intensity of the field in which it is placed. In order to compare the strengths of magnetic fields by the relative densities of the lines of force, it is assumed that a field of unit strength contains one line of force per square centimetre.

The earth itself is practically a huge misshapen or irregular magnet, and behaves as such, acting as if its poles were situated relatively near, but actually at some distance from, the geographical poles. If a magnet needle were suspended so that it could turn freely in a *vertical* plane, it would, with a plane of rotation east and west, point vertically downwards with its north pole; but if the plane of rotation were north and south, the needle would, in London, come to rest with the north-seeking pole dipping downwards, and making an angle—known as the angle of inclination or dip—of about 67½° with the horizon. If another magnet were suspended or balanced on a pivot in a horizontal plane, the needle would set itself approximately north and south, the north-seeking pole pointing to the north magnetic pole of the earth. The axis of the magnet—that is, the straight line joining its two poles—would actually make an angle—known as the angle of declination—of about 18°, with the geographical meridian passing through its centre. It will be observed that there is here a case of attraction between the north pole of the earth and the north-seeking pole of the magnet; but this is no contradiction of the law that similar poles repel and dissimilar attract, inasmuch as the magnetic properties of the north pole of the earth are in all respects the same as those of the south-seeking pole of a magnet. The earth's total magnetic force can be resolved into two components at right angles to each other, one acting in a vertical direction, tending to depress the north-seeking pole of the needle, the other acting in a horizontal direction and striving to make it point north and south. Their relative values may be found by the familiar parallelogram of forces (see fig. 49). The line A B is drawn making an angle θ with the horizontal equal to the angle of inclination, and the right-angled parallelogram which has A B for a diagonal completed with its sides horizontal and vertical. Then, if A B represents in length the magnitude of the total magnetic force, A C and A D will be proportional to the horizontal and vertical components respectively.

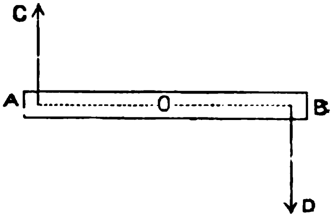
FIG. 49.



When the magnet is so balanced that it can only move in a horizontal plane, then a large proportion of the force—viz. the vertical component—is simply exerted in pressing the magnet on its support. The remainder, or the horizontal component only, is effective in making the magnet point towards the magnetic north and south. On the other hand, when the plane of a dipping needle is at right angles to the magnetic meridian, or to the direction of the earth's lines of force, the vertical component only is active, and the magnet points vertically downwards, the horizontal component spending its force in pressing the pivots against their bearings, vainly striving to urge the needle round into the direction of the dip. A horizontally balanced magnetic needle is useful in pointing out the direction of these north and south magnetic poles of the earth.

In consequence of the immensity of the earth as a magnet, its magnetic field is practically uniform over any small space—that is, its lines of force are *parallel* and *equidistant*. It follows, therefore, that the poles of a needle floating on water are attracted or repelled with equal force in any position, and, as a consequence of this, the needle does not move bodily towards the north pole of the earth, but is simply directed so as to point north and south. It may be stated that it is a well-known law in mechanics that when two equal forces, parallel but opposite in direction, act at the ends of a rigid bar, they tend to turn it round its centre. The turning effect is greatest when the forces act at right angles to the bar, as do C and D in fig. 50, A B being the rigid bar. The amount of this turning effect M is equal to the sum of each of the two forces multiplied by its distance from the centre—that is,

FIG. 50.



$$M = (C \times O\,A) + (D \times O\,B);$$

whence, C being equal to D,

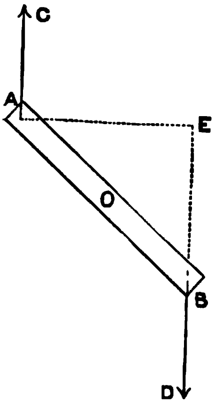
$$M = C(O\,A + O\,B)\text{—that is, } M = C \times A\,B,$$

or the product of one of the equal forces into the perpendicular distance between them.

Such a pair of equal forces is called a couple, the perpendicular distance between their direction being called the arm of the couple; and the turning effect, M, as measured by the product of one of the forces into the arm. is the moment of the couple. As the bar turns round or rotates, the moment M is decreased, th forces being the same but acting at less advantage—in oth words, the *leverage* is reduced. This will be more evident from consideration of fig. 51, where the moment of the couple C × A E, the new perpendicular between the forces.

Reverting once more to the experiment with the floating needle, if we call the strength of one of the poles of the needle and let H represent the horizontal component of the earth's magnetic field, the the force acting on each end of the need is $m \times$ H. If we place the needle so as t point east and west, the arm of the coup is equal to the full length l of the needl whence the moment is $m \times$ H $\times l$. Th moment decreases as the needle mov round towards zero, or that position which it is pointing north and south. Th moment is then reduced to nothing, becoming $m \times$ H $\times$ o, because the length the arm is nothing; consequently, needle remains at rest.

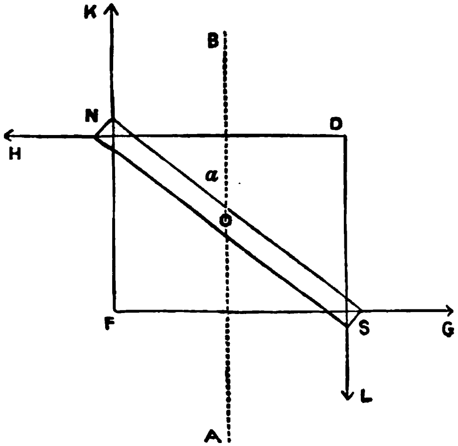
FIG. 51.



Now, we can cause any current, strength of which we may desire to measure, to develop a field strength f, at right angles to the earth's directive force—that is say, we can cause the current to travel north and south, and so doing deflect a magnetic needle from its zero position. Th the new force acting on each end of the needle will be $m \times f$, whe m is the strength of the magnet pole; and, the length of the ar being calculated as before, the moment will be $m \times f$ multipli by that arm. Manifestly, the needle will come to rest when th moment of the couple due to the current is equal to that due the earth.

Let the needle N S (fig. 52) be so deflected by a curren and make an angle, N O B, called the angle of deflection, with th magnetic meridian A B. This angle N O B is, of course, equal t the angle N S D. Let this angle be called $a°$, and let f be th strength of the field due to the current, the direction of the actio f which is indicated by the arrows D H and F G. D S is then e perpendicular distance between these directions, whence the oment of the couple due to the current is $m \times f \times$ D S.

FIG. 52.



By similar reasoning it will be seen that the moment of the uple due to the earth is $m \times$ H $\times$ N D. Now, if the needle has umed a state of rest, showing that the moments of these two uples are equal, it follows, as a matter of course, that

$$m \times f \times \text{D S} = m \times \text{H} \times \text{N D},$$

d (by cancelling and dividing)

$$f = \text{H}\,\frac{\text{N D}}{\text{D S}}.$$

The ratio $\frac{\text{N D}}{\text{D S}}$ is called the tangent of the angle N S D, which, ain, is equal to the angle of deflection a°—that is to say,

$$f = \text{H} \tan a^\circ.$$

This strength of field, f, is proportional to the current producing ; therefore the current, C_1, is likewise proportional to H tan a°.

And this will be true of all currents and all deflections, so that we let a second current, C_2, cause the needle to be deflected rough the angle b°, then C_2 must be proportional to H tan b°.

Consequently, $C_1 : C_2 :: H \tan a^\circ : H \tan b^\circ$,

that is, $C_1 : C_2 :: \tan a^\circ : \tan b^\circ$,

or the two currents are directly proportional to the tangents of th angles through which they deflect the needle. By referring to table such as is here given, we can find the numerical value of th

TABLE OF NATURAL SINES AND TANGENTS.

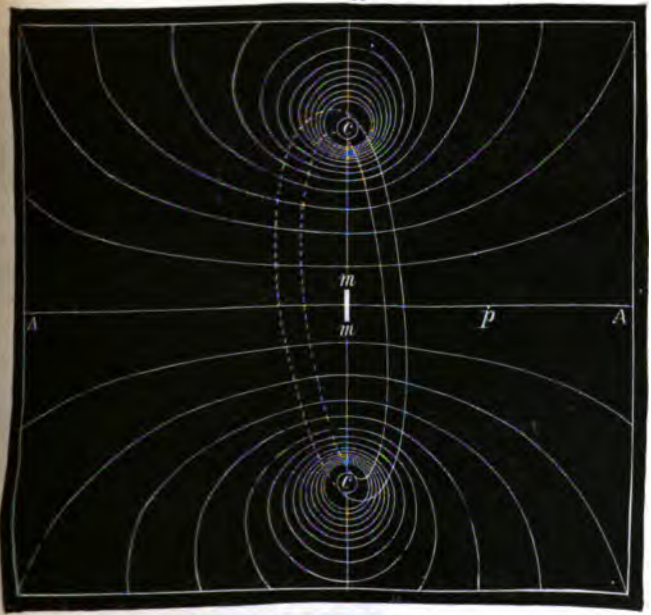
Deg.	Sine	Tangent	Deg.	Sine	Tangent	Deg.	Sine	Tang
1	·017	·017	31	·515	·601	61	·874	[illegible]
2	·035	·035	32	·530	·625	62	·883	[illegible]
3	·052	·052	33	·544	·649	63	·891	[illegible]
4	·070	·070	34	·559	·674	64	·899	[illegible]
5	·087	·087	35	·573	·700	65	·906	[illegible]
6	·104	·105	36	·588	·726	66	·913	[illegible]
7	·122	·123	37	·602	·753	67	·920	[illegible]
8	·139	·140	38	·615	·781	68	·927	[illegible]
9	·156	·158	39	·629	·810	69	·933	[illegible]
10	·173	·176	40	·643	·839	70	·939	[illegible]
11	·191	·194	41	·656	·869	71	·945	[illegible]
12	·208	·212	42	·669	·900	72	·951	[illegible]
13	·225	·231	43	·682	·932	73	·956	[illegible]
14	·242	·249	44	·694	·965	74	·961	[illegible]
15	·259	·268	45	·707	1·000	75	·966	[illegible]
16	·275	·287	46	·719	1·03	76	·970	[illegible]
17	·292	·306	47	·731	1·07	77	·974	[illegible]
18	·309	·325	48	·743	1·11	78	·978	[illegible]
19	·325	·344	49	·755	1·15	79	·981	[illegible]
20	·342	·364	50	·766	1·19	80	·985	[illegible]
21	·358	·384	51	·777	1·23	81	·987	[illegible]
22	·374	·404	52	·788	1·28	82	·990	[illegible]
23	·391	·424	53	·798	1·33	83	·992	[illegible]
24	·407	·445	54	·809	1·37	84	·994	[illegible]
25	·422	·466	55	·819	1·43	85	·996	[illegible]
26	·438	·488	56	·829	1·48	86	·997	[illegible]
27	·454	·509	57	·838	1·54	87	·998	[illegible]
28	·469	·532	58	·848	1·60	88	·999	[illegible]
29	·485	·554	59	·857	1·66	89	·999	57·
30	·500	·577	60	·866	1·73	90	1·000	Infi

tangents of these or other angles, and so can easily compare strength of the currents.

An instrument which will enable us to make these comparis is called a tangent galvanometer; but in order to obtain accur results one important point must be carefully attended to designing the instrument, for the foregoing proof only holds goo when the two forces forming a pair act parallel to each other

And every position of the needle. This means, in short, that field due to the earth, and that due to the current, must be orm throughout the entire space in which the needle can be ed. Fortunately, we can, by using a very short needle, make space proportionally small, and thereby render the problem er. The earth's field, as has been already stated, is uniform, that due to a current is far from uniform, more particularly

53.



the immediate vicinity of the wire, consequent on the very ecided curvature of the lines of force. However, as we get rther away from the wire, these lines approximate more and ore to straight lines, and if we bend the wire into a ring of large ameter we shall find a small space at its centre where the lines force are, to all intents and purposes, straight and parallel. In g. 53 is shown a horizontal view of the ring and of the distribu-on of the lines of force in the field. The two ellipses represent the ring itself, of which *c c* are the horizontal sections an A A the axis. The magnetic needle is indicated by *m m*. If we, therefore, suspend the small needle here, the necessary condition for a tangent galvanometer are satisfied; the needle being to short to permit of its poles being moved into an irregular o variable part of the field.

With a ring 6 inches in diameter we can, in fact, use a needl three-quarters of an inch in length without the risk of introducing any sensible error.

Such a ring of wire, then, with a needle suspended at centre, will serve to compare and measure current strength according to the law which we have just stated, i.e. each current will b proportional to the tangent of the angle through which it can deflect the needle. When made in a practical form, the tange galvanometer is one of the most useful pieces of apparatus at o command.

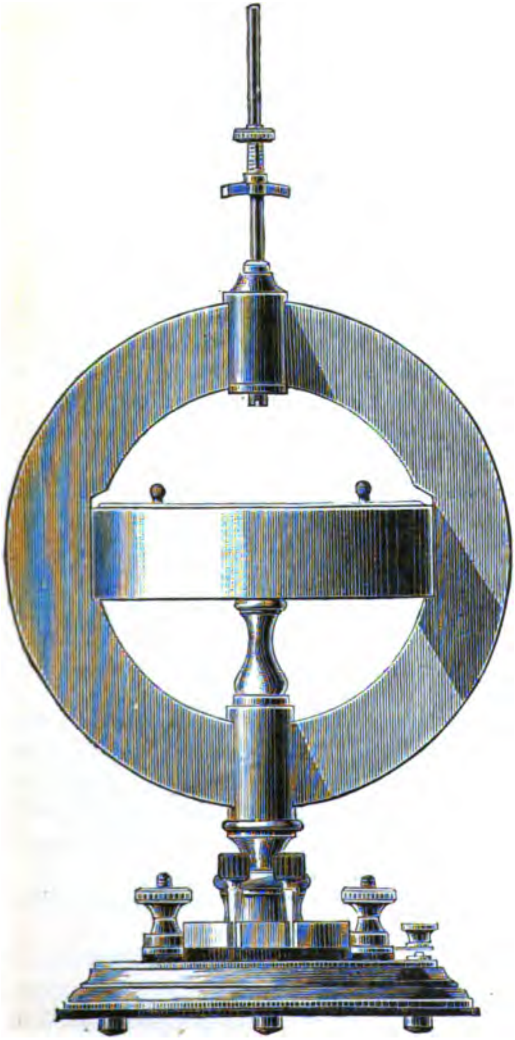
It is important to notice here that a variation in the streng of the magnetic needle will introduce no error in the readi for if, for instance, a needle loses its magnetisation or beco weak, it is acted upon more feebly both by the earth and current, and in the same proportion, so that the weakened e of the earth's field is balanced by the equally weakened effect the current's field.

Proceeding now to a consideration of the laws governing construction of the instrument, it is essential to remember the force with which a current deflects the needle is proportio to the length of the wire, and inversely proportional to the squ of its distance from the needle. But if we increase the size of coil, we not only increase the distance from the wire to the nee but also increase the length of the wire in exact proportion to increase of the radius. Now the former reduces and the la increases the effect; the joint result is that the force with whi the needle is deflected varies inversely as the radius of the coil the same current.

If, therefore, we use one coil of 3 inches radius, and anot of 6 inches radius, the deflection will be the same when the curre in the larger coil is double that in the smaller.

With, however, a single turn of wire 6 inches in diameter, o

FIG. 54.



mparatively strong currents can affect the needle, and, as we ve seen, we are prohibited from reducing this diameter for the purpose of obtaining a sensible deflection with comparatively wea currents. But this difficulty can be easily overcome, for we ca increase the length of the wire, without increasing the distanc from the needle, by the simple device of coiling it round the needle a number of times. Since the effect on the needle varies directly as the length of a wire, and the length of a wire of two turns is double that of one turn, the effect on the needle is doubled also; in other words, the effect on the needle varies directly as the number of turns of wire in the coil. It follows that, with equal currents, a 6-inch coil of one turn will give the same deflection a a 12-inch coil of two turns.

It must be remembered, however, that if the number of convolutions is increased to any great extent the resistance becom considerable, and the very act of inserting the galvanometer in a circuit may decrease the current we desire to measure.

Bearing all these points in mind, we will now consider a real practical instrument for the measurement of current streng selecting for description the pattern which is undoubtedly the b yet constructed—viz. the Post-Office tangent galvanometer. general view of the instrument is shown in fig. 54.

The casing is of brass. The mean diameter of the coi $6\frac{1}{2}$ inches; the width of the channel in the brass ring which co tains the wire is $\frac{5}{16}$ inch, and its depth $\frac{1}{8}$ inch. The length of needle, which is carefully pivoted with agate on an iridium poi is $\frac{3}{4}$ inch.

As this needle is too short to indicate its own deflections, carries a light pointer of gilt copper wire, about 5 inches in lengt fastened to it at right angles. This pointer moves over an e graved circular scale plate, one half of which is divided in degree the other half into divisions corresponding to the tangents of tho degrees, as shown in fig. 55.

It may be of service to some if we refer here to the manner i which this tangent scale is constructed.

Let the quadrant O L (fig. 56), represent a portion of the circ along which the scale is to be marked, and let C O be the radi along which the index needle is to point when at rest and wh no current is circulating through the coil of the instrument. Th draw the tangent line, O D, that is to say, a line at right angles

O C, meeting it in O. Then mark off along O D any number of equal divisions, and project lines from those points or divisions to C, the centre of the circle, intersecting the quadrant at various places. These points of intersection will then correspond to the equal divisions along O D, and will be proportional to the tangents of the various angles which would be measured at those intersections. This device saves the operator the trouble of ascertaining from a table the 'tangent' equivalents to the various deflections and then calculating their relative values.

FIG. 55.

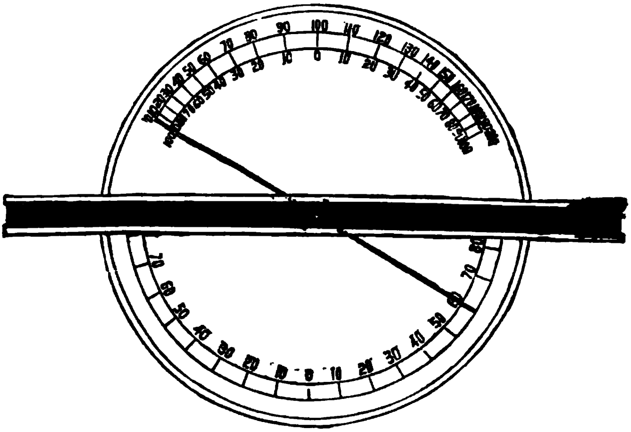
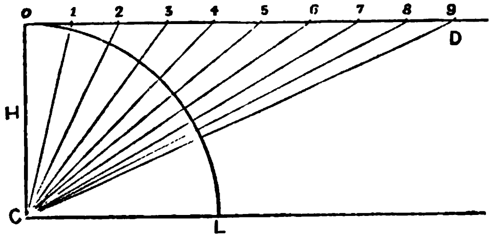


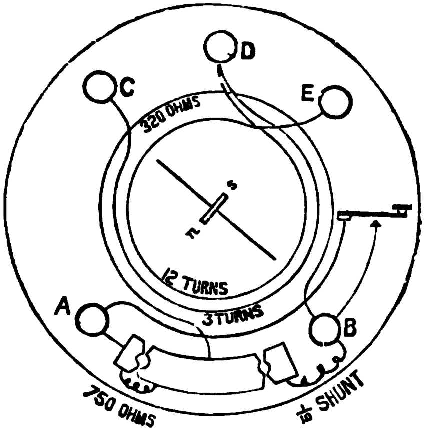
FIG. 56.



A piece of looking-glass is placed under the scale-plate and is exposed at two circular slots in the plate, so that in taking a reading the observer may let the pointer cover its own reflection, when he will be assured that he is looking vertically down upon it, avoiding thereby any error due to parallax—that is to say, any inaccuracy in reading caused by looking at the pointer sideways. A lever, operated by a small switch extending through the box which carries the needle and scales, is provided for lifting the needle off its pivot when not in use. There is also a small adjustable magnet which slides on a brass rod over the needle, and is used for varying the sensibility of the instrument. This may appear to be a step backwards from the beautifully simple thesis upon which the instrument is constructed. If there were no good reason for introducing this 'controlling' magnet to vary the sensibility of the instrument, the wisdom of its introduction would be questionable. But it must be remembered that there are several hundreds of these instruments in use throughout the country, and if it is known that a reading of twenty-five divisions corresponds in every case to a current of 1 milliampere, the direct value of any other reading can be confidently estimated. The controlling magnet, when placed with its S. pole over the N. pole of the needle, assists the directive force of the earth's magnetism and reduces the sensibility, and *vice versâ*. Either effect may be varied by sliding the magnet up or down the rod. For instance the needle will move from zero with the weakest current when the magnet is placed at the bottom of the rod with its poles opposing the earth's magnetism.

A reference to fig. 57 will make the conception of the electrical portion of the instrument easier. There are three separate coils of wire in the brass ring, or bobbin, the ends of each being brought down through the hollow pillar and connected under the base of the instrument to their respective terminal screws, as shown in plan on the figure. Between the terminals C and D is a coil consisting of three turns of thick wire; between D and E are twelve turns of similar wire, wound in the opposite direction. If the current be sent from C to E, we get nine turns acting on the needle, for three of the twelve turns are neutralised by the three in the opposite direction between C and D. The resistance of these coils is negligibly low, so that we are able to get the effect from three, nine, or twelve turns without varying he strength of the current. The other coil consists of a great nany turns of fine silk-covered wire. Its resistance is exactly 20 ohms. One end of it is joined to terminal B, and the other nd to the middle brass block. By inserting a brass plug in the

FIG. 57.



ft-hand hole, the end of the coil attached to the middle block is onnected to terminal A direct. If, however, this plug is removed, e current in travelling, say, from B, has to pass through an dditional resistance coil of 750 ohms (which is fixed under the ase of the instrument) before it reaches terminal A. Under these ircumstances the total resistance between A and B is 1,070 ohms. uppose now a single Daniell cell, whose resistance is comparavely low, to be joined to terminals A and B. By Ohm's law the urrent is equal to $\frac{1\cdot07 \text{ volts}}{1{,}070 \text{ ohms}}$, or ·001 ampere—that is, 1 millimpere.

These resistances are, in fact, calculated for use with a single aniell cell as a standard. We can always immediately produce deflection which we know to be that due to 1 milliampere f current, and find the value of any other current by observing ts deflection under similar conditions. A small key is fixed on he base of the instrument; when depressed it connects A and B as will be seen from fig. 57, or, in the usual language, it short-circuits the coils. It is used for checking the oscillations of the needle and bringing it quickly to rest.

It is sometimes required to measure a current so strong that the deflection is inconveniently high. In this case a part of the current may be 'shunted,' or provided with an alternative path, or, more correctly speaking, a by-path, so that only a portion of the current shall go through the galvanometer, the rest going through the shunt. It is necessary, however, to know exactly what fraction of the total current is passing through the instrument and what through the shunt. If we join the ends of the coil by a shunt equal to it in resistance, then the current will divide equally between the two paths, and only half of the total current will be measured. If the resistance of the shunt be $\frac{1}{9}$ that of the galvanometer, then $\frac{9}{10}$ of the current will pass through the shunt and the other tenth through the galvanometer. In this case, therefore, the total current will be ten times that measured by the deflection of the needle.

The instrument we are now describing is provided with such a shunt ; its resistance is $\frac{320}{9}$ ohms, and fig. 57 clearly shows how it may be brought into play by inserting a plug in the right-hand hole, thus connecting together the middle and right-hand blocks. Suppose, when the adjustment is such that 1 milliampere gives twenty-seven tangent divisions, that we insert this tenth shunt, and then with a current of unknown strength obtain eighty-one divisions. The current flowing round the galvanometer is manifestly 3 milliamperes, but this is only $\frac{1}{10}$ of the whole, consequently the total current is 30 milliamperes.

In order to reduce the current flowing through a galvanometer to any fraction of its full value, say, to $\frac{1}{n}$, the resistance of the shunt necessary to produce that result must be $\frac{1}{n-1}$ that of the galvanometer. A moment's reflection, however, will make it evident that the introduction of a shunt reduces the resistance of the circuit, and may, therefore, cause a considerable and material increase in the current strength. Where this increase of strength is appreciable, the introduction of extra resistance sufficient to compensate for the fall caused by the shunting becomes necessary, the problem being to ascertain exactly how much compensating resistance is required. By the laws of the joint resistance of two parallel wires, explained in Chapter II, the joint resistance of the galvanometer, G, and the shunt, S, will be equal to $\frac{GS}{G+S}$. Now, the resistance of S has just been shown to be $\frac{1}{n-1}$ part of G, or $\frac{G}{n-1}$, that is, if only a tenth of the current is to pass through the galvanometer, the shunt resistance should be $\frac{1}{10-1}$ part of the galvanometer resistance G. That is to say, $S = \frac{G}{n-1}$, and inserting this value we get—

$$\frac{GS}{G+S} = \frac{G\frac{G}{n-1}}{G+\frac{G}{n-1}},$$

which is equal to $\frac{G}{n}$.

So that the joint resistance of a galvanometer coil of 320 ohms and its tenth shunt will be $\frac{G}{n} = \frac{320}{10} = 32$, whence it follows that the reduction in resistance due to the use of the shunt amounts to $G - \frac{G}{n}$, or $320 - 32 = 288$. 288 ohms is, therefore, in this case the resistance that it would become necessary to introduce in order to restore the resistance ot the circuit to the same value that it had prior to the introduction of the shunt. And, generally, it may be said that the introduction of a shunt reduces the resistance of the circuit to the extent of $\frac{n-1}{n}$ G, and that amount of resistance will need to be inserted to re-establish the conditions of the circuit. In short, this compensating resistance is equal to the difference between the resistance of the galvanometer alone and of the galvanometer shunted.

When great accuracy is desired, all the readings on the tangent galvanometer should be taken with the needle deflected as nearly as possible through an angle of 45°. The reason for this is, that any given variation in the strength of the current will produce a greater effect on the needle when it is in that position than when in any other, or, in other words, the sensitiveness of the instrument is then at its maximum. For instance, if, when the needle were deflected through 45°, an increase of the current by one-twentieth gave an increase of half a degree in the deflection, a similar increase in the current when the needle stood at 10° or 80° would not be indicated at all, or rather, the deviation would not be discernible.

Every galvanometer has a definite *angle of maximum sensitiveness*, or such an angle of deflection that with a small accretion of current there will be a larger divergence than when the needle is at any other point on the scale. The mathematical demonstration of the existence of this angle would be somewhat beside the scope of this work, but we may repeat that for every tangent galvanometer the angle of maximum sensitiveness is 45°. We should always endeavour, therefore, when using this instrument to get the deflection as near 45° as possible, or when comparing two currents get the deflections at equal distances on either side of this point. It has already been pointed out that it is very convenient, we would say more, it is necessary, in practice to be able to determine immediately the value in amperes or milliamperes, to which some particular deflection of the needle corresponds, and it will be remembered that with a Daniell cell as a standard a current of 1 milliampere may be immediately produced.

The Latimer-Clark cell is less liable to variation and is much more trustworthy than the Daniell when used with a very high external resistance. Although, in order to obtain the most accurate results, this cell should only be employed in those tests where it is not allowed to send any current at all, its portability and the fact that it is always ready and in good order are such important advantages that it is frequently used in such a test as the preceding, under conditions which, perhaps, render it no more accurate than the Daniell. Its resistance, which is as a rule considerable, should be known, and, by using an extra coil, the resistance in circuit can then be made 1,435 ohms. The electromotive force of one of these cells being 1·435 volt, it follows hat through the resistance of 1,435 ohms it will yield a current of exactly 1 milliampere, or,

$$\frac{1{\cdot}435}{1{,}435} = {\cdot}001 \text{ ampere.}$$

The foregoing applies to a galvanometer with a tangent scale constructed so that its zero point is in the centre, as is the case with the *inner* scale on the tangent divisions side in fig. 55. But it will be seen that in this figure there is an outer scale also of tangent divisions, but with the zero point at the extreme left-hand, where the pointer is shown resting. This outer scale is known as the 'skew scale,' from the position of the needle when at zero, and its great advantage lies in the fact that the range of measurement is double that of the ordinary scale. For a comparatively high reading, also, the deflection can be read with greater ease as the pointer is not in the part of the scale where the divisions are close together. It is true that a small deflection cannot easily be read, but the ordinary scale can be employed for this if necessary.

Unfortunately, the tangent galvanometer is but little suited for the measurement of very powerful currents such as those generally employed in electric lighting. We must, therefore, now direct attention to an instrument which will answer this purpose, and one which is beautifully simple in its conception, and at the same time remarkably accurate and free from error. It is based upon the simple experiment mentioned at the commencement of this chapter, viz., the attraction or repulsion which takes place between two wires carrying currents. It may now be stated that the force of this attraction or repulsion is readily measurable, being, in fact, proportional to the strength of one current multiplied by the strength of the other, provided that the distance between the two wires remains constant. If we suppose the currents in each of the wires to be exactly equal, say 2 amperes, then the force may be represented by the number 2 × 2 = 4. Now if we double the current strength in each wire, the force of attraction or repulsion will be 4 × 4 = 16; in other words, when the current strength in each is doubled, the force between them is quadrupled. Similarly, if we treble the current in each wire, or make it 6 amperes, then the mutual force will be 6 × 6 = 36, or nine times as great as when the current was 2 amperes. We therefore see that the force of attraction or repulsion between two wires carrying equal currents varies as the square of the current strength. It will be apparent that the simplest method of obtaining equal currents in each wire is to join them in series, and send the same current through both of them in succession. Then, if any number of currents be sent through them, the force of the action between the wires will be proportional to the square of the strength of the current in each case, whence it may be reasoned that if these forces can be measured or compared, the currents producing them can also be estimated; for as the force varies as the square of the current, the current will vary as the square root of the force exerted by it.

In constructing an instrument on this principle, it is necessary, therefore, to have some means of accurately measuring the force exerted, and also to ensure that the distance between the wires remains exactly the same during all the comparisons.

The *Siemens dynamometer* fulfils all these conditions to the letter. A general view of this instrument is given in fig. 58, fig. 59 showing the manner in which the principle is applied. The two wires (or coils) are rectangular in shape. One of them, A B C D, is rigidly fixed to a vertical support, while the other, E F G H, which is sufficiently large to embrace the fixed wire, when the plane of the one is at right angles to that of the other, is suspended by a stout silk thread.

In the actual instrument this movable coil consists of a single turn of thick wire; and in order that the current may be passed through it, without in any way impeding or interfering with its freedom of motion, its two ends, G and H, are brought round and bent down into mercury cups placed vertically one over the ot [illegible] so that the two ends and the point of suspension, K, are in t [illegible] same vertical line.

Connection with the mercury is made by a wire passing in [illegible] the bottom of the cup. The arrows in fig. 59 show the directi [illegible] of the current in the various parts of the circuit, when a current [illegible] sent through both coils in series, and it is easy to see that each vertical limb of the movable coil will be urged, by repulsion on one side and attraction on the other, to set itself in the same

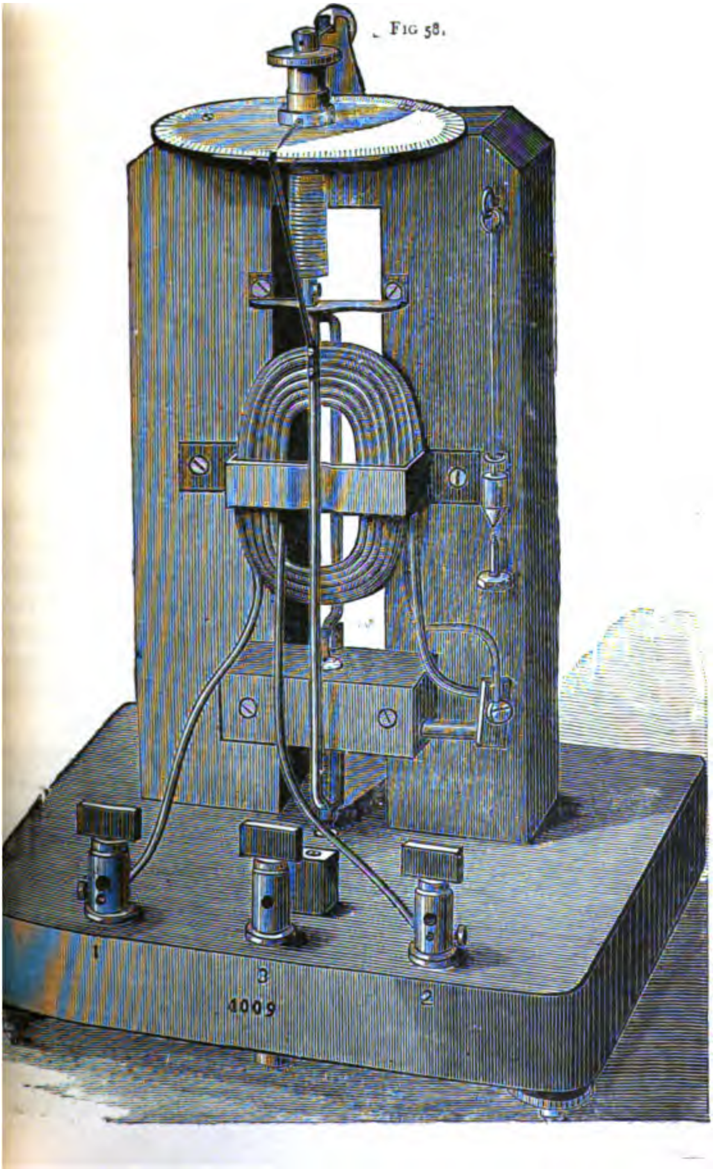
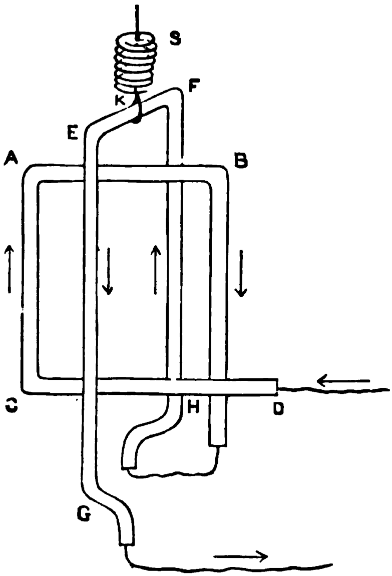


FIG 58.

plane as the fixed coil. But it has already been said that i essential that the coils should remain or be brought back into t same relative positions when the force between them is measure In the Siemens dynamometer the position selected is with th planes of the two coils at right angles ; and the force measured i that force which is necessary to keep the movable coil in thi position against the action of the current.

This antagonistic force is applied by means of a spiral spring, a the lower end of which is rigidly fixed to the rectangle E F G H; while its upper end is fixed to a mill-headed screw, which can b turned round, torsion bei thereby applied to the spi spring. A pointer is at- tached to the screw-he and moves with it, an travelling over a graduat scale, divided usually in 400 equal divisions insta of 360 degrees, indicates t amount of torsion appl to the spiral spring in bri ing the coil E F G H back t the zero position, against th opposing force due to th current circulating in th coils. It is a simple an well-known law that the forc of torsion is proportional to the angle of torsion, and as the angle through which th screw is turned in order to keep the movable rectangle at zero is an exact measure of the torsion applied, the force necessary to the production of that angle must be proportional to the force acting between the two coils, and due to the current circulating in them. This latter force varies, as we have seen, as the square of the current strength, so that, therefore, the current is proportional to the square root of the angle of torsion. The movable coil also carries a pointer, the end of which just over-

FIG. 59.



laps the scale-card and plays between two pins about half an inch apart. When it points to zero, the two coils are accurately at right angles one to the other.

The instrument has usually two separate and distinct fixed coils; one consisting of a few turns of thick wire, and the other of a larger number of turns of thinner wire. The object of this arrangement is to facilitate the measuring of currents differing very considerably in strength, and so to increase the available range of the instrument. One end of the thin-wire coil is joined to the left-hand terminal screw (fig. 58), and one end of the thick-wire coil to the right-hand screw. The other two ends are connected to the upper mercury cup, while the lower cup is joined to the middle terminal screw.

For a very strong current, then, the centre and right-hand terminals, giving the thick-wire and movable coils, should be used; while for a weaker one, the centre and left-hand terminals, between which are the thin-wire and movable coils, should be employed.

On account of the operation of the law of the square, a more accurate reading can be obtained in the higher part of the scale than in the lower, and it is therefore, where possible, more advantageous to use the thin-wire coil for such currents as would give only a low reading with the thick-wire coil.

Three levelling screws and a level are provided, it being absolutely essential that the coils should be exactly perpendicular. The movable rectangle can be raised or lowered by means of the thread which is attached to a screw at the top of the instrument, until it moves quite freely and makes good contact with the mercury. It is difficult to replace this silk thread quickly, and this constitutes a weak point in the instrument, for an inexperienced operator frequently commences his experiment by breaking it.

The instrument requires calibration, that is to say, it is necessary to find out to what current strength a certain amount of torsion is equivalent, before any unknown current can be measured in amperes. This calibration may be effected by deflecting the rectangle by a current of known strength, and then by turning the milled-head attached to the upper end of the spiral spring, applying just sufficient torsion to restore the pointer attached to the rectangle to the zero position. Suppose the current to be one ampere and the torsion applied 16 divisions. Then if a curr of unknown strength be sent through the same coil, and it necessary to apply 64 divisions of torsion to bring the rectan back to zero, the latter current will be 2 amperes strength; for

$$C_1 : C_2 :: \sqrt{16} : \sqrt{64},$$

that is as 4 is to 8, or as 1 is to 2.

In practice such calculations would be exceedingly inconve nient; the makers, therefore, calibrate the instrument, or dete mine what strength of current corresponds to the various angl of torsion, both for the thin- and thick-wire coils. These resu are tabulated in a convenient form and supplied with the inst ment.

On referring to fig. 59 it will be observed that, if the current reversed, the rectangle will still be deflected in the same directi because, the direction of the current in *all* the sections be altered, attraction or repulsion will take place between the s limbs as before.

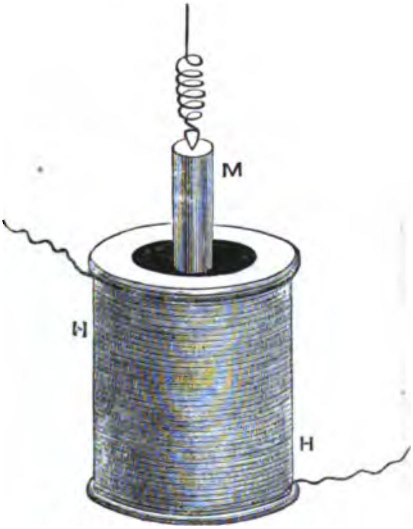
The instrument can therefore be used to compare ei positive or negative direct currents, or even alternating curre —*i.e.* those whose direction is rapidly reversed. The po attached to the screw-head should always stand at zero when instrument is not in use, otherwise the spiral spring will take *set* and will not bring the rectangle to zero when the pointe brought there. The spring will, however, gradually recover f any such set if it be not excessive.

The Siemens dynamometer is a very accurate instrument w used with ordinary care, but every measurement occupies a cert amount of time, for in every case the rectangle has to be brou back exactly to zero, the amount of torsion noted, and then table referred to, to ascertain the current strength to which torsion corresponds. It is evident that an instrument wh immediately indicates in amperes the strength of the curr flowing is far more convenient to use, although, unfortunat a *direct-reading* instrument has not yet been designed which be relied upon for any length of time to be as accurate as Siemens dynamometer.

For portability and the rapidity with which measurements be taken, Ayrton and Perry's ammeter (or ampere-meter) stands in the front rank.

It is based upon the fact, that a piece of soft iron placed in a magnetic field which is not uniform, will be urged from a comparatively weak into the strongest part of the field. One way of viewing the action is to consider the iron, M (fig. 60), as a magnet for the time being, and then if the field be generated by a current circulating round a helix of wire, H H, and the iron is placed just outside the helix, it will be sucked down until it reaches the middle of the helix, which is the strongest part of the field. Now, this action will be proportional to the product of the strength of the field and the strength of the temporary magnet; as the latter varies with the strength of the field, but not according to any regular law, the readings will not be proportional to the current strength unless by some means the strength of this temporary magnet is kept constant. Experiment shows that although the magnetic lines of force pass readily through a piece of iron when there are very few lines already there, yet, when a great many are present, any further addition to their number becomes very difficult. When in this latter condition the iron is said to be 'saturated.' A piece of *very thin* soft iron tubing becomes saturated even in a weak field, that is, in a field traversed by but few lines of force; so that beyond a certain stage, although the strength of the field is increased, the number of lines of force passing through the iron tubing, that is, its strength considered as a magnet, remains practically the same. Therefore, if we use a

FIG. 60.

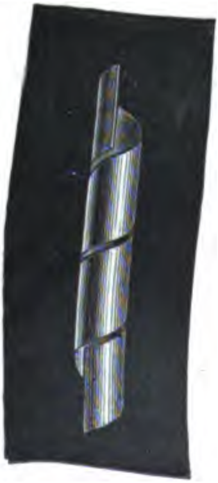


very thin tube of soft iron, the force with which it is sucked into the helix will, for all fields above a certain strength, depend simply upon the strength of the field and will be proportional thereto, and consequently, also proportional to the strength of the current producing the field.

Except for weak currents, then, we may estimate the strength of a current by measuring the pull on such a thin tube of iron placed partly inside a helix. It must not be placed exactly in the middle of the coil, as that, being the strongest part of the field, is the position of rest for the iron.

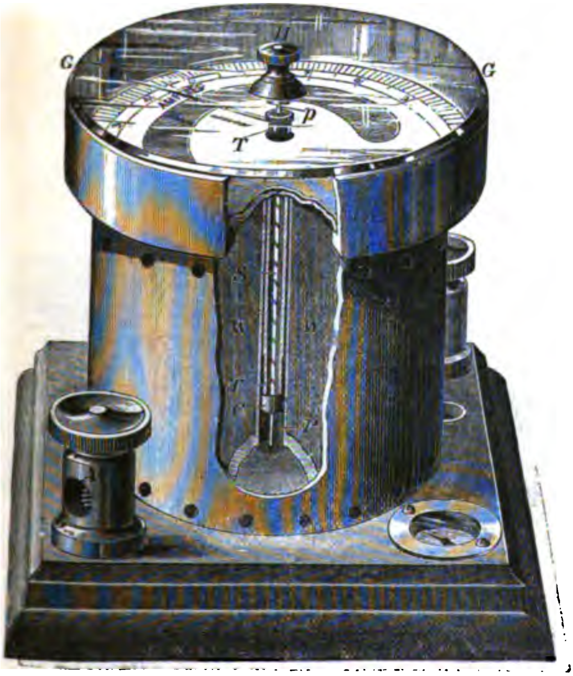
In the instrument under consideration the method of measuring the pull is unique. It depends upon a peculiar property possessed by a flat spiral spring shaped like a curled-up shaving, as illustrated in fig. 61. If such a spring be stretched while one end of it is fixed, the other end will rotate, and the angle of rotation will be exactly proportional to the amount of stretching, the angle being considerable for a small extension of the spring. A reference to fig. 62 will show how these principles are combined in the actual instrument.

FIG. 61.



The helix fills the space marked W W, and is composed of stout wire offering little resistance, so that its introduction into a circuit does not diminish the current flowing therein. T is the thin tube of soft iron which is sucked down more or less by the current, its lateral movement being prevented by two small brass pins, P and p. The former is fixed to a small piece of brass, C, which is fastened to the bottom of the soft iron tube. The spiral spring is placed inside this tube, its lower end being rigidly fixed to C and its upper end to the brass pin p. As p is also rigidly connected to the screw-head, H, the upper end of the spring cannot rotate, therefore when the tube T is sucked down the lower end of the spring rotates, carrying with it the tube. The upper end of the tube which projects out of the coil carries a nter which moves over a graduated scale, and so indicates the gle of rotation, the usual horizontal mirror being provided to id parallax. The scale is divided into equal divisions repre- nting amperes and fractions of an ampere, but as the iron does t become saturated until the current has attained a certain ngth, the first portion of the scale is never used, and is, in fact, t graduated, for, as has been explained, the indications at this e are not proportional to the current strength. It is clear that he iron tube moved through any considerable distance so as to into a part of the field of different strength, the readings would be proportional; but it will be remembered that the peculiarity the spring is that the angle of rotation is great for a very small ension in length, consequently the pointer traverses the whole

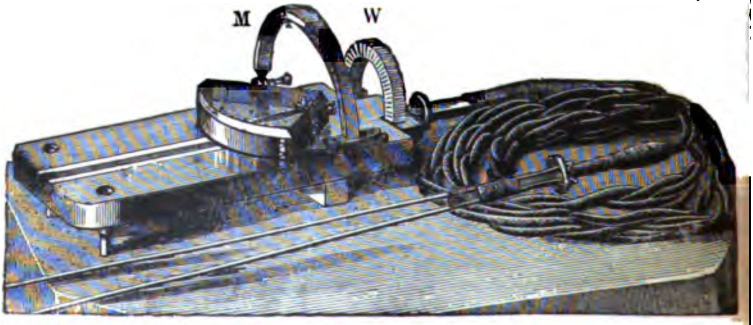
FIG. 62.



range without the distance through which the iron moves being sufficient to cause inaccuracy. The instrument is calibrated by the maker, similar scale-cards having equal divisions being used for all instruments of the same range, and the adjustment effected by shifting a small auxiliary coil. When a current is sent through the instrument the pointer indicates at once the number of amperes of current flowing, thus avoiding calculation or reference to a table Occasionally, however, comparison should be made with some reliable standard, such as a Siemens dynamometer, for the instrument is liable to variation after continued use.

The pointer moves in the same direction, no matter in what direction the current is sent through the coils, because the magnetism of the iron tube is also reversed. There is a possibility here of an error being caused by the retentivity of the iron, but as it is so thin and soft its magnetism is readily completely reversed, and no error is introduced from this cause. In order to indicate the direction of the current a small magnetic needle is usually fitted in the base-board, and its blue-coloured end points towards the terminal screw at which the current enters. The pointer can be adjusted to zero by turning the milled head H. The coils and tube are surrounded by an iron casing, which, as will be explained hereafter, prevents any external currents or magnets affecting the tube and so causing inaccuracy in the readings.

FIG. 63.



Sir William Thomson has designed several forms of current-measuring instruments, one of the best being that illustrated in fig. 63, and known as the graded ammeter. It may be regarded as a form of tangent galvanometer, the coil-ring, W, consisting of one or more turns of stout copper wire or ribbon. The magnetic needle is very small and delicately balanced, and carries a long light pointer which travels over a scale in the bottom of the sector-shaped case or box. A controlling magnet, M, semicircular in shape, is fixed to this box, which slides in a V-groove in the base of the instrument. This magnet is somewhat powerful, sufficiently so, in fact, to overpower the effects of terrestrial magnetism, whence, the magnet moving with the needle, a practically constant field is maintained in any and every position in which the instrument may be placed.

When in the zero position the needle, coil, and magnet are in the same vertical plane. A scale is let into the base, along the edge of the groove, to facilitate the necessary calculations. The object aimed at in this method of construction is to provide an instrument capable of measuring current strengths of considerable difference, for it is evident that as the needle is withdrawn from the plane of the coil the effect of a given current upon it diminishes rapidly. The relative effect of a current upon the needle at different distances from the coil is proportional to the cube of the radius of the coil divided by the cube of the distance between the needle and the wire itself, that is, as $\frac{r^3}{b^3}$, where r is the mean radius and b the mean distance between the wire of the coil and the needle. This distance, b, is the hypotenuse of a right-angled triangle, whose base, a, is the axial distance between the needle and the plane of the coil, the perpendicular being the mean radius, r. These latter distances are more easily measured than b, and we may write the expression $\frac{r^3}{b^3}$ as $\frac{r^3}{(\sqrt{r^2 + a^2})^3}$.

Apparatus of this class cannot be used in the neighbourhood of dynamos or other large masses of moving iron, although it is often used in the laboratory. One great objection to it is the tedious calculation which has to be made for every reading. The controlling magnet is another source of trouble in consequence of its liability to vary. In order that the wires conveying the current shall not affect the reading, the main leads are connected to two long pieces of wire which are twisted together for a considerable distance as shown in the figure, so that each neutralises the tendency of the other.

We come now to the consideration of a class of ammeters, simple in construction and action, independent to a great extent of the proximity of extraneous electro-magnetic fields, and, being direct-reading instruments, they are exceedingly useful as dynamo-room indicators, telling the attendant at a glance whether or not his current is being maintained at its proper value. A number of these instruments depend upon the power of a coil alone, to raise a more or less weighty piece of iron against the force of gravity, while others have a solenoid and core to perform a similar operation. They all require to be calibrated, but, under the circumstances, that is not objectionable providing the calibration is correctly performed.

FIG. 64.

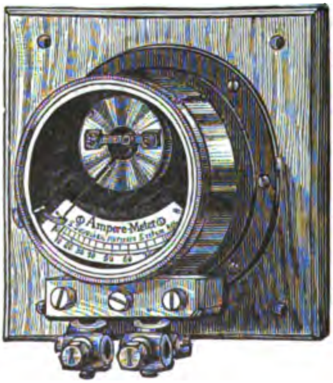
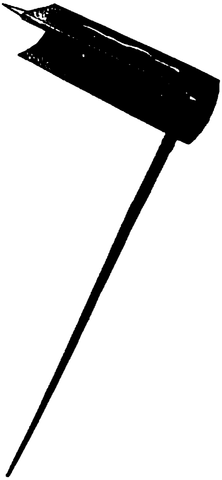


FIG. 65.

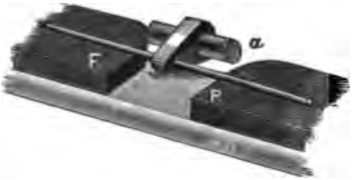


The first instrument of this class to which we will refer is that constructed by Schuckert. A general view of this ammeter is shown in fig. 64, and a view of the moving portion of it in fig. 65. It will be seen that the instrument is made to be fixed against a wall with its base in a vertical position, the working parts being protected by a circular metal case with a glass front. From the two terminal clamps below the instrument case, stout metal bands are led to the solenoid, which is placed with its axis horizontal, and consists of single copper casting, with helical saw-cuts, so as to lead the current a few times round the 'needle.' With such a solenoid, which is designed for very heavy currents, no insulating material is employed other than the air; but in the case of instruments constructed for the measurement of weaker currents, the solenoid is made of a number of turns of ordinary stout insulated wire. A light steel arbor or spindle is pivoted so as to lie parallel to, and a little to the left of, the axis of the coil. It has attached to it a thin curved plate of soft iron shaped as shown in fig. 65. This piece of iron is nearly equal in length to the arbor, and extends through the length of the solenoid. A light aluminium pointer is also fixed to the arbor at right angles, and the movable parts are so weighted that, in the absence of a current, the pointer is held in the zero position by the force of gravity.

When a piece of iron is placed in a solenoid, but out of centre, the effect of a current is to bring the iron towards the centre. Therefore a current passing through the coil of the Schuckert instrument, in endeavouring to rotate the curved piece into the centre, raises it against the force of gravity, through a distance depending upon the strength of the current. The index attached to the arbor travels, therefore, over the scale which is placed behind it, and thus indicates the strength of the current passing through the instrument. As may be imagined, the divisions of the scale are unequal, but the scales of all instruments of the same range are exactly alike, the centre of gravity of the moving parts in each case being adjusted to suit the scale. The adjustment is made by bending a small piece of copper wire (see fig. 65) fixed at one end to the upper side of the arbor, but this operation is a matter of some difficulty when it is desired to reproduce a previous calibration. It is an interesting fact that the gross weight of the moving part is but $\frac{1}{36}$ of an ounce. The amount of friction is therefore very slight, and, there being very little in the instrument which is liable to vary with ordinary workshop usage, it is a useful and practical piece of apparatus.

The instrument known as the 'Gravity' ammeter is the invention of Mr. S. F. Evershed; it is manufactured by Messrs. W. T. Goolden & Co., and is for practical work an excellent and reliable measuring instrument.

FIG. 66.

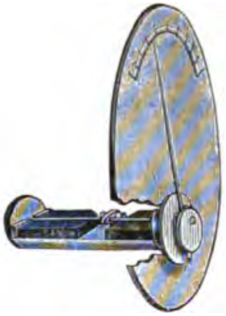


In this case also the magnetising coil is placed with its axis horizontal, and in the middle of it there lies a small cylindrical piece of soft iron, *a* (fig. 66), which is fixed, by means of a piece of brass, to a brass arbor, this arbor being pivoted at its extremities, and weighted so as to keep the small iron rod in the position shown. F and P are two small soft iron slabs, placed end to end, but just sufficiently far apart for the small iron rod, *a*, to swing freely between them.

The coil encircles these slabs, the arbor, and its attachments; and when a current passes through it, the lines of force gather up into the slabs, and pass lengthways along them, say from P to F, with the result that there is a very dense field just between their opposing ends.

In its normal position the small iron rod, *a*, lies almost outside this dense field, and we have seen that a piece of iron so situated is always urged from a weak part towards the strongest part of the field. Consequently, the iron piece, *a*, is drawn down against the restraining force of gravity which acts on the counterbalancing weight, and, as an increase in the current strength will add to the number of lines and to the force of attraction, the distance through which the iron piece is moved may be made to indicate the current strength. But the depression of the iron rod is not proportional to the increase in the current, consequently an ordinary degree scale, or any other equally divided scale, cannot be employed. Reverting for a moment to the construction of the instrument, it should be explained that, as shown in fig. 67, the two iron slabs (P, F, fig. 66) are fixed upon a stout brass strip, the remote end of which carries a brass disc forming one bearing for the arbor. At the near end of the strip is a larger disc, provided with a hole through which the spindle freely passes, having also ixed to it a smaller brass disc which forms the other bearing for the arbor. Between these two last-mentioned discs is a space sufficient for the pointer to swing freely throughout its range, and a small arm is also attached to the arbor, its end being tapped to fit a small nut which acts as the counterpoise, keeping the pointer at zero when no current is passing through the coils. The scale plate is vertical, so that the instrument, which in appearance resembles the voltmeter pictured in fig. 108, can be placed against a switchboard or wall, and its indications conveniently read. The calibration is carefully performed, and a separate scale is made for each instrument, instead of the instruments being altered to suit a common scale, with more or less accuracy, as is frequently done.

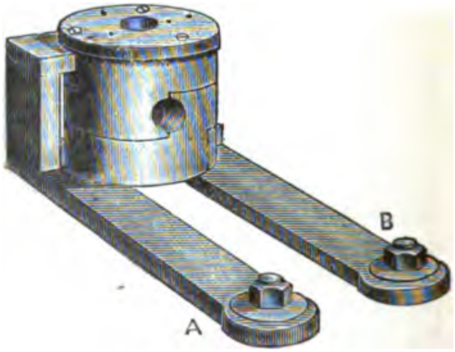
Fig. 67.



The ends of the iron slabs on the further side, as viewed in fig. 66, are curved slightly, and by altering this curvature, the force with which the iron rod is attracted in any given position can be varied. This enables the scale to be made to suit the work for which the ammeter is intended; for instance, an instrument whose range of measurement is from 20 to 200 amperes may be required for use on a circuit where the working current should never rise above 130 nor fall below 90 amperes, and in such a case it might be necessary to be able to measure exactly the value of the current between those limits, while the upper and lower parts of the scale would simply be used to indicate with certainty the fact of the current being either considerably too high or too low.

In such an ammeter the slabs would be so shaped that a given increase in the current strength would move the iron rod through a much greater distance when near the middle of its swing, than an equal increase would move it when it is near the zero position, or the extreme end of its journey. Consequently, on calibrating the instrument, we should obtain a scale open in the centre, and closed at the ends—that is to say, with much larger divisions in that part where the most accurate measurements are required to be made. On the other hand, the scale could, if required, be made open at the ends and closed in the middle, or, in fact, varied at any part to suit special requirements. For comparatively low currents the magnetising coil is wound with thick insulated copper wire, but for heavy currents, such as from 200 to 1,000 amperes, a specially constructed coil is employed. If the conductor has any appreciable resistance, such heavy currents develop a considerable amount of heat, and a cotton or silk insulating covering, besides impeding radiation, is very liable to get damaged. The best insulator is air, which is practically a perfect non-conductor, and indestructible, and has the advantage that it moves away when at all heated, its place being taken by colder air; the insulating material thus tends to keep the conductor cool instead of preventing the escape of heat, and only in very exceptional cases does the irregular dissipation of heat by the air currents introduce any error. Fig. 68 illustrates the magnetising coil employed to carry heavy currents. It consists of a massive cylindrical tubular casting of copper, the central hole being just large enough to admit the brass strip with the slots, &c., shown in fig. 67.

FIG. 68.



It is divided by saw-cuts to form a 'coil.' The current, entering, say, by the straight connecting bar A, passes up the vertical strip to the top of the cylinder, and thence round the coil from back to front. It then passes down to the next convolution at the left of the drilled hole, where this particular saw-cut terminates, and thence round the coil again to the beginning of the third convolution, at the right of, and underneath, the drilled hole. After again going round the coil the current leaves by the bar B. It thus takes about 2½ complete turns round the coil, which, with a current of 300 amperes, would give 750 ampere turns.

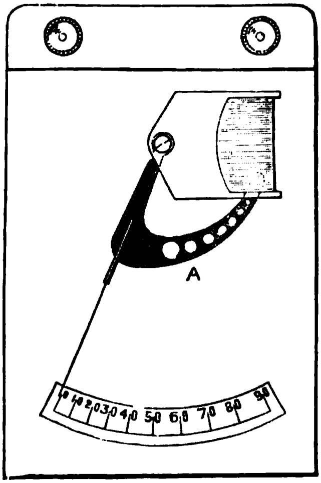
It will be evident that such a coil has very little resistance, and that therefore the power absorbed and the amount of heat developed in it will be correspondingly small. The instrument may consequently be kept continuously in circuit without any risk of damage or serious waste of energy. The bars by which connection is made are long and straight, to prevent the current in the leading wires affecting the 'needle,' for without these precautions a considerable error might, owing to the small number of convolutions, be introduced. In an instrument for measuring 1,000 amperes the 'coil' consists of a massive cylinder divided on one side by a radial saw-cut, with the straight connecting bars placed in a line with each other. In this case the current makes but ¾ of a turn round the needle, thus again giving, with 1,000 amperes, 750 ampere turns.

There is one possible source of error with instruments of this description due to the retentivity of the iron, but by exercising great care in the selection and treatment of the metal, this error has been practically eliminated. The iron, in fact, is not touched by a tool after it has been annealed, the film of oxide formed during that operation being simply dissolved by immersion in an acid. Perhaps the best way of testing for inaccuracy due to this cause is to take two sets of readings, one with ascending values of the current from zero to the maximum, and the other with corresponding descending values. Any retentivity of the iron would cause the latter set of readings to be higher than the former, but in these instruments the results are practically identical.

It is not so easy to accurately measure a current of several hundred amperes as it is to measure a few amperes or a fraction of an ampere, but all these ammeters are calibrated by having their full current passed through them, and its effect, as indicated by the pointer, carefully observed.

The required current strength is obtained by means of secondary batteries, which are charged in series and joined up in parallel for discharging, and in order to ensure greater accuracy a definite fraction only of the whole current is measured. For example, if it is desired to calibrate an ammeter which is capable of measuring from 40 to 400 amperes, it is joined up with the secondary battery, and a set of 100 rather stout iron wire resistances, these wires being all joined up in parallel, and placed so as to have equal facilities for cooling. A standard ammeter is joined up in circuit with one of these iron wire resistances, and a length of the iron wire equal in resistance to that of the ammeter is removed, so that this compound branch, formed of a portion of iron wire and the ammeter, is equal in resistance to each of the other 99 branches consisting only of iron wire. This standard ammeter is calibrated with extreme care, and as the main current divides equally among the 1 branches, the ammeter accura measures one-hundredth of it; that for the maximum current 400 amperes it is only necess to measure 4 amperes—a co paratively easy matter. For 1,0 amperes it would thus be necessa to measure only 10; but an ammeter designed to measure such a high current is conveniently calibrated by joining in series with it two 500-ampere meters which are themselves connected together in parallel.

FIG. 69.

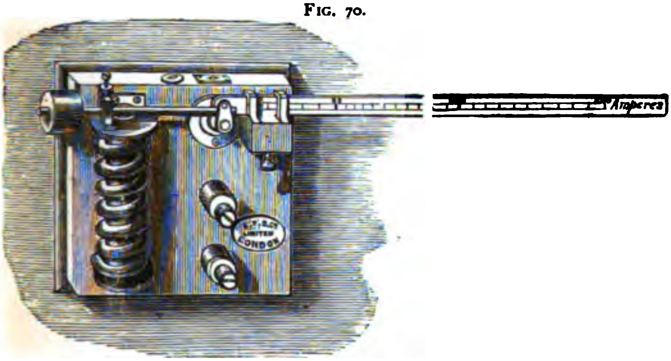


The absence of a portable instrument which will stand a little rough usage has hitherto restricted the measurement of alternating currents to such rather inconvenient instruments as the Siemens dynamometer, but it has recently been discovered that by slightly altering the proportions of the iron parts, these gravity ammeters answer admirably for measuring alternating currents, the difference in the readings caused by any variation in the rate of alternation within the limits which obtain in electric lighting (that is, from about 50 to 120 alternations per second) being practically *nil.*

A simple form of gravity ammeter is that shown in fig. 69, and made by the Société des Téléphones de Zurich. The indicating needle is attached to a peculiarly shaped tongue of very thin soft sheet iron, A, which is furnished at intervals with a number of holes. These holes afford a means of adjusting the sensibility of the instrument and making the scale open near any desired reading. As the current passing through the coil increases in strength the tongue is drawn up into the bobbin and the needle made to pass over the scale on the face of the instrument.

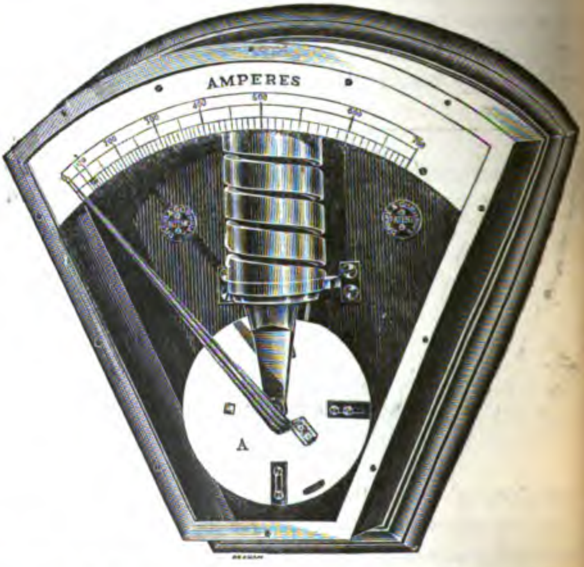
The 'Steel-yard' ammeter, made by the Electrical Power Storage Company and illustrated in fig. 70, is a useful and interesting piece of apparatus. It consists of a coil of thick wire, which, for heavy currents, is simply a copper rod bent into a spiral and enclosing a soft iron core, which, on being magnetised, attracts a soft iron armature attached to one end of the steel-yard lever. A sliding weight is suspended from the other arm of the lever, its position being adjusted until it just balances the force of attraction between the core and its armature. This instrument is very convenient from the fact that its sensitiveness can be varied in several ways, such as varying the weights, &c. The range can also be varied by varying the length of the lever. The range of each instrument is considerable, the one illustrated being designed to indicate from 50 to 250 amperes.

FIG. 70.



The 'Disc' ammeter of Messrs. Drake and Gorham (fig. 71) is another useful and simple instrument. It consists of a spiral of copper ribbon enclosing a soft iron core, having for its armature a soft iron disc A. When the pointer stands at zero, as shown in the figure, the centre of gravity of the disc is just below the suspending pivots, which are carried by two pieces of brass attached to the core, the disc rotating between them. A small segment of the disc is cut off so as to form a slight prominence, which serves as a means of, to some extent, concentrating the magnetic lines of force at a definite point. As the strength of the current increases the attraction of this portion of the disc causes the heavier section to be raised against the force of gravity. A light non-magnetic index needle is fixed to the disc, and as the latter rotates the needle travels over a clear open scale.

FIG. 71.



The lineman's detector (figs. 72 and 73) is a very handy instrument when used for tracing circuits and localising faults, but it must not be regarded as a measuring instrument. It consists of ordinary instrument bobbins, mounted vertically, and each nd with two coils of wire, one consisting of a few turns of thick e and the other of many turns of fine wire. The former is ally wound to 0·2 ohm, and the latter to about 100 ohms. A unt coil is sometimes added to the thick wire coil to reduce its nsitiveness. The magnet is about an inch long, and is mounted

FIG. 72.

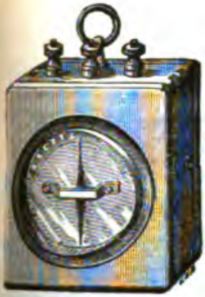


FIG. 73.

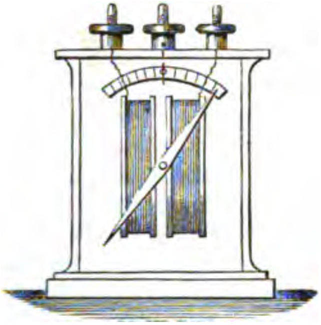


FIG. 74.

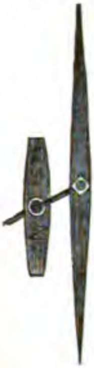
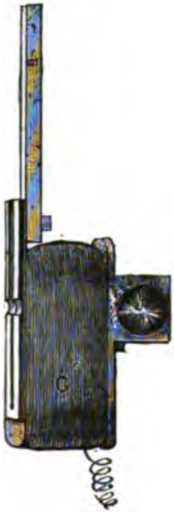


FIG. 75.



on a horizontal axis (see fig. 74), so that it can turn freely inside the coils, a long non-magnetic indicating needle being also fixed on the front end of the spindle and moving over a graduated dial. Sometimes a soft iron needle is substituted for the magnetised steel one, it being magnetised by the induction of two powerful steel magnets fixed to the bobbins, one of which is shown at *m* in fig. 75. These magnets can be curved so as to fit into a case of ordinary dimensions.

One end of each of the coils is connected to one or other of the outer terminals on the top of the case, the other two ends being both joined to the centre terminal. Constructed as described, the needle should be deflected through 40° or 50° by a current flowing through the thin wire coil of 9·3 milliamperes—that is to say, by a single Daniell cell having an internal resistance of 7 ohms. The thick wire coil should, with the same cell giving a current of 139 milliamperes, cause a deflection of 20° to 30°.

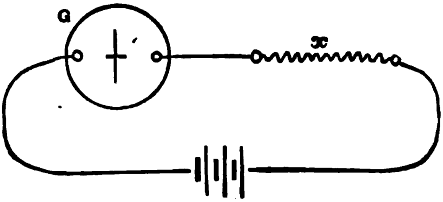
CHAPTER V.

MEASUREMENT OF RESISTANCE.

WHEN the difference of potential in volts between the two ends of a wire is known, and also the current in amperes which that difference of potential is able to maintain in the wire, then the resistance of that wire in ohms may easily be calculated, for by Ohm's law it is equal to the number of volts divided by the number of amperes, or $R = \frac{E}{C}$, where E stands for the electro-motive force in volts, C for the current strength in amperes, and R for the resistance in ohms. If, for instance, a difference of potential or an electro-motive force of 15 volts between the two ends of a wire were able to maintain a current of 2 amperes through it, then its resistance would be $\frac{15}{2} = 7{\cdot}5$ ohms. But if the resulting current were only 2 milliamperes, then the resistance would be $\frac{15}{{\cdot}002} = 7500$ ohms. With one of the instruments described in the preceding chapter, the current flowing may be measured, and in the next chapter we shall show how the difference of potential between any two points of a circuit may be measured in volts; and this method is perhaps the very best that can be devised for finding the value of very low resistances. But sometimes we know the maximum difference of potential or electro-motive force which a certain current-generator can produce, and this knowledge will enable us in certain cases to calculate resistance after merely measuring current strength.

If we have a battery of which we know the electro-motive force, say 10 volts, and also the internal resistance, say 20$^{\omega}$, we may use it to send a current through the tangent galvanometer, G, and the unknown resistance, x, by joining them all in series as shown in fig. 76. Suppose the resulting current to be 20 milli-amperes as measured by the tangent galvanometer, then we may find the *total* resistance of the whole circuit by dividing the electro-motive force by the current. The total resistance will be $\frac{10}{\cdot 02} = 500^{\omega}$. Now, the resistance of the battery and galvanometer is 340^{ω}.; if we subtract this from the total resistance we get the value of the unknown resistance, x, that is, $500 - 340 = 160$ ohms.

FIG. 76.



By using the thick wire coils of the galvanometer, and a battery of very low resistance as compared with that of the unknown resistance, no serious error will be made by ignoring the resistance of the battery and galvanometer, and regarding the unknown resistance as the total resistance of the circuit. Under these conditions a number of fairly high resistances may be easily compared, for the same electro-motive force will send through each a current which is inversely proportional to the resistance. Thus, if with three resistances, a, b, c, we get deflections of 30, 25, and 60 tangent divisions respectively, then, $a : b : c :: \frac{1}{30} : \frac{1}{25} : \frac{1}{60}$,

that is, $a : b : c :: 10 : 12 : 5$.

Presuming the galvanometer to be so adjusted that a deflection of 30 tangent divisions is obtained when a current of 10 milli-amperes is passed through the thick wire coil, and the battery employed to have an electro-motive force of 2 volts, then the resistance of $a = \frac{2}{0{\cdot}01} = 200^{\omega}$. Therefore, the resistance of $b =$

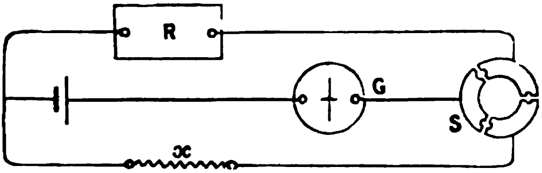
240°, and of c = 100°. As previously stated, however, the resistance of the battery and of the galvanometer must be taken into account, unless they are very low indeed as compared with the unknown resistances.

It should here be observed that in most of the tests to be described it is necessary that a set of resistances whose values are known exactly should be provided. The accuracy of the results obtained depends, in a very great measure, upon the accuracy of the values given to these resistances, so that great care should be exercised in their manufacture, measurement, and use. In Chapter II. some of the principal causes of inaccuracy were enlarged upon, and it was shown how, by avoiding them, a reliable set of resistance coils might be produced.

Assuming such a set of coils to be available, let us now discuss its utility in helping us to ascertain the resistance offered by other conductors.

If a wire, whose resistance we desire to ascertain, is joined up with a battery and galvanometer, the current flowing will deflect

FIG. 77.



he galvanometer needle through a certain angle ; let this angle be ccurately noted. Then, if the unknown resistance is removed rom the circuit, and a box of coils of known resistance inserted in ts place, this same deflection may be reproduced by varying the mount of resistance introduced by means of the plugs or arms, s described in Chapter II. The current then deflecting the eedle will manifestly be exactly the same in strength as in the irst case, and therefore (since the electro-motive force of the attery is unaltered) the total resistance of the circuit must be the ame as before. Hence the resistance in the box is equal to the nknown resistance. A convenient way of taking this test is shown in fig. 77. R is the set of resistance coils, x the unknown resistance, and S is a three-way plug switch, consisting of three pieces of brass, any two of which may be joined together by inserting a brass plug in the holes provided for the purpose between them. By means of this switch, either x or R may be rapidly placed in circuit, and it is advisable to take a second test after R has been adjusted, to make sure that the electro-motive force of the battery has not been altered by polarisation and so have varied the value of the test. The galvanometer, G, should be a sensitive one; it should, in fact, under all conditions indicate the alteration in the current strength, caused by the addition or subtraction of the coil of lowest value in the resistance-box. As by this method the same deflection is reproduced, any form of galvanometer will answer the requirements, providing only that it is sufficiently sensitive.

Supposing, however, a tangent galvanometer and a battery, both of very low resistance, to be available, the currents which the battery can send through a known and an unknown resistance can be compared directly by the deflections of the galvanometer needle, for if there are, say, 50 tangent divisions in the first case and 45 in the second, and the known resistance is 32 ohms, then

$$45 : 50 :: 32 : x,$$

because the deflection in each case will be inversely proportional to the resistance in circuit. Hence, $x = 35{\cdot}\dot{5}$ ohms. The three-way plug switch may be used as in the last test, but both readings should be taken near the 'angle of maximum sensitiveness,' viz. 45°.

When, however, the resistances of the battery and galvanometer are comparatively high, their values must be known or ascertained, and allowed for in accordance with Ohm's law as follows: Let the resistance of the galvanometer, G, be 320^{ω}, that of the battery $r = 12^{\omega}$, and the known resistance $R = 560^{\omega}$; let the current with R in circuit (C_1) give 50 tangent divisions, and with x in circuit (C_2) give 45 tangent divisions.

Then, in the first case,

$$C_1 = \frac{E}{R + G + r}, \text{ whence } C_1(R + G + r) = E,$$

and in the second case,

$$C_2 = \frac{E}{x + G + r}, \text{ whence, also, } C_2(x + G + r) = E,$$

therefore $$C_2(x + G + r) = C_1(R + G + r),$$

whence $$x = \frac{C_1}{C_2}(R + G + r) - G - r.$$

Since $\frac{C_1}{C_2}$ is merely a ratio, the strength of the currents in milliamperes need not be known, the number of tangent divisions produced by the currents being inserted instead of C_1 and C_2. Inserting all the values, then, we get

$$x = \frac{50}{45}(560 + 320 + 12) - 320 - 12$$
$$x = 659{\cdot}\dot{1} \text{ ohms.}$$

The resistance of the galvanometer is nearly always known and engraved on the instrument, but it is frequently necessary to measure the resistance of the battery at the time of making the test. To avoid this it is better to use a battery of very low resistance, and this may usually be obtained by joining up several sets in parallel.

The equation will then stand:

$$x = \frac{C_1}{C_2}(R + G) - G.$$

By inserting the values as before we can see the amount of the error caused in this case by ignoring the battery resistance of 12 ohms.

$$x = \frac{50}{45}(560 + 320) - 320$$
$$x = 657{\cdot}\dot{7} \text{ ohms.}$$

The error is thus but 1·3"; and it is not difficult to get a battery of only about ·1 ohm resistance to send a sufficiently strong current for the above test, when the error would be negligibly small.

This method also provides us with a means of measuring the resistance of a galvanometer. For, let the second reading be taken through a known resistance $K = 700^{\omega}$ instead of x, then ignoring the battery resistance, it follows that, as before,

$$C_1(R + G) = C_2(K + G)$$
$$C_1R + C_1G = C_2K + C_2G$$
$$G(C_1 - C_2) = C_2K - C_1R$$
$$G = \frac{C_2K - C_1R}{C_1 - C_2}.$$

Inserting the values we get

$$G = \frac{45 \times 700 - 50 \times 560}{50 - 45} = 700 \text{ ohms.}$$

With the same apparatus the internal resistance of the batter may be measured. For if the battery is joined up to the lo resistance coil of the galvanometer (three or twelve turns), practically the only resistance in the circuit will be that of the battery If possible, the adjustable magnet should be placed so that th deflection is, say, 50 tangent divisions. Now, it will be evide that to *halve* the current flowing, the resistance in the circuit mus be *doubled*. If, therefore, resistance R is inserted until the defle tion falls from 50 to 25 divisions, the resistance R will be equal t the resistance x of the battery.

Sometimes, however, the effect of the controlling magnet insufficient to produce a convenient deflection, and it is the necessary to introduce some resistance in the first test, say P, f this purpose. Then

$$C = \frac{E}{x + P}, \text{ or } C(x + P) = E.$$

If, now, P is increased to R in order to halve the deflectio and therefore halve the current strength,

then $$\frac{C}{2} = \frac{E}{x + R}, \text{ or } \frac{C}{2}(x + R) = E,$$

therefore $$\frac{C}{2}(x + R) = C(x + P),$$

whence $$x = R - 2P.$$

For instance, if with a low-resistance galvanometer it is found necessary to insert 11 ohms in order to bring the deflection down to 60 divisions, and to increase this resistance to 31 ohms in order to make the deflection 30 divisions, then the resistance of the battery $x = 31 - 22 = 9$ ohms.

In some cases the resistance of a cell is so very low that it becomes a difficult matter to measure it with great accuracy. Secondary cells, especially, have not only a low resistance, but also a comparatively high E.M.F., so that some special method is necessary in dealing with them, if great accuracy is desired.

A very pretty method consists in allowing the cell to send a current through a low external resistance of known value, and then measuring the fall of potential which takes place along this resistance. This fall can be easily found by subtracting the external potential difference from the total E.M.F. developed. As the resistance of each portion of the circuit is proportional to the fall of potential taking place along it, the internal resistance of the cell can then be deduced. One of the hot-wire voltmeters (page 189), designed to indicate up to 2·5 volts, is a useful piece of apparatus for this work. The total E.M.F. of the cell can be measured by joining the voltmeter to the cell terminals, because the high resistance of the voltmeter allows only a feeble current to be generated, so feeble, in fact, that the fall of potential inside the cell is exceedingly low; whence the potential difference indicated is practically equal to the E.M.F. developed. If a second external conductor, but of low resistance, is also joined to the terminals of the cell, the total external resistance will be considerably reduced, and the fall of potential inside the battery proportionally increased, and a lower E.M.F. will be indicated by the voltmeter. Consequently, if we denote the total E.M.F. by E, the fall of potential in the external and internal portions of the circuit by P and p respectively, the resistance of the cell by r, and of the known external resistance by R, it is evident

$$\mathrm{E} - \mathrm{P} = p,$$

and

$$\mathrm{P} : p :: \mathrm{R} : r;$$

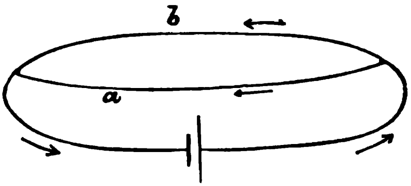
from which we get

$$r = \frac{p\,\mathrm{R}}{\mathrm{P}}.$$

When a battery of such cells is to be measured—say twenty—it is better to reverse nearly half of them—in this case, nine; then the resistance to be measured is that of twenty cells, while the E.M.F. urging a current through them is only that of two cells.

The method next to be described depends upon the fact that if two conductors of exactly equal resistance are joined up 'in parallel' and placed in a circuit, as shown in fig. 78, the current will divide equally between the two—that is, the current in *a* will be exactly equal to the current in *b*. The converse of this holds good, viz. if we have two conductors so joined up in parallel, and we know that the current in *a* is exactly equal to the current in *b*, then we are certain that the resistance of *a* is exactly equal to the resistance of *b*.

FIG. 78.

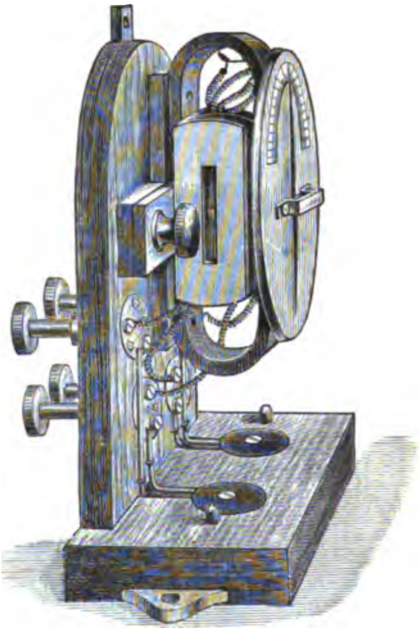


The 'Differential Galvanometer' is an instrument for showing when the currents in two branch circuits are equal. In principle it is very simple. It consists of a magnetic needle, either pivoted horizontally or vertically, surrounded by *two* distinct coils of wire of exactly equal resistance, and wound so as to act with equal force on the needle. If, therefore, a current is sent through one coil, and a current of equal strength through the other *in the opposite direction*, their effects will be neutralised one by the other, and the needle will not be deflected. Figs. 79 and 80 illustrate a really good form of differential galvanometer, for ordinary work, which is used in the telegraph service.

The soft iron needle is vertical, but the arrangement for keeping it strongly magnetised is somewhat peculiar.

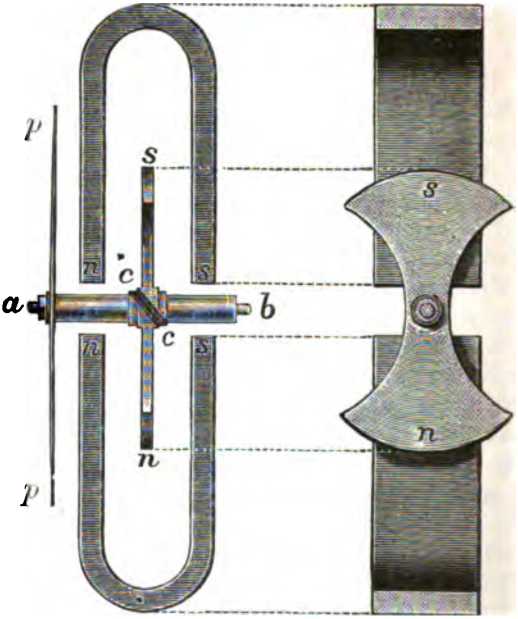
Fig. 80 shows side and front elevations of the needle and magnets. The spindle, which is pivoted at *a* and *b*, is rather massive, and a piece of brass is inserted obliquely at *c c*, as shown, thus breaking its magnetic continuity. Each half of the needle, *n s*, is fixed at right angles to one half of the spindle at this point, and the whole is embraced by two horse-shoe magnets, placed with their like poles adjacent, as shown in the figure. These magnets form a very strong field in the space in which the spindle lies. A large number of the lines of force pass through the spindle, but when they reach the break in the iron at *cc* they bend upwards through the soft iron needle from one side, and downwards from the other side, the result being that the needle is a powerful magnet with its north pole downwards. On the end of the spindle is fixed a blackened brass pointer, *pp*, which, passing over or in front of a circular dial divided into degrees, indicates the movements of the needle. The two wires, each offering 50° resistance, are wound side by side over two separate bobbins, so that the corresponding portions of each wire are equally disposed in relation to the needle and exert equal magnetic effects upon it. This method is, of course, far in advance of the old instrument-makers' method of winding one wire alone on one bobbin and the other on another bobbin. The tests for a differential galvanometer are that, if powerful but equal currents are sent in opposite directions through the coils, no effect should be produced upon the needle: each coil used separately should produce equal but opposite deflections with the same current, and the coils should offer exactly the same resistance. The inner ends of the two wires on the bobbins are respectively joined together and the other four ends connected to as many terminals

FIG. 79.



on the back of the instrument. This allows the current to be sent through the coils in several ways. First through one coil only, resistance 50^{ω}. Secondly, through both coils in series in such a direction that they act upon the needle in the same manner, when the resistance will be 100^{ω} and the deflective action doubled, provided the increase of resistance does not sensibly reduce the current. Thirdly, through both coils in parallel and in the same direction; the resistance in this case will be 25^{ω}, and the deflective action the same as that of *one* coil only. Fourthly, through both in parallel, but in opposite directions, when the needle should, as already stated, be unaffected. Lastly, through both coils in series in opposite directions, when the needle should also be unaffected. This last method of joining up is also useful for proving if the deflective effects of the two coils are

FIG. 80.



equal, for the same current passes through each irrespective of their resistance.

Although the wires are wound side by side throughout, it is very rarely that they are found to act with equal force on the needle. There are three ways of attaining this result without affecting the resistance. The position on the bobbins of a portion of either or both of the wires may be altered; or a part of the wire which has the greater effect may be unwound and wound back on the bobbin in the opposite direction; or the stronger may be unwound until an exact balance is obtained, when the length so unwound may be coiled up in the base of the instrument, where, if wound 'double,' it will have no effect on the needle.

The lower end of the needle is weighted, to keep it in the vertical position and to restore it to that position on the cessation of the current; and the current acts against this weight when it deflects the needle. The *arm* at which this weight acts increases with the deflection of the needle, so that the angle of deflection cannot be proportional to the current strength. The relation between the two is, in fact, irregular, because of the peculiar shape of the needle (shown in fig. 80), and because the field due to the current, although almost uniform inside the coil, is far from being so near the edges and just outside.

But at present we shall only consider the use of the instrument with the needle at or near zero, at which point, it may be mentioned, it is most sensitive.

Provided with this instrument, a battery, and a set of resistance coils of sufficient range, we are in a position to rapidly measure unknown resistances.

Fig. 81 shows the best way of making the connections. G is the galvanometer, R a set of resistance coils, x the unknown resistance, and K a key for closing the battery circuit. On depressing the key, the current will divide at a c, the junction of the two coils of the galvanometer, part passing through the coil $a\,b$ and R, and the remainder through the other coil $c\,d$ and x, back to the battery.

Supposing R to be of less resistance than x, then a greater part of the current will pass through $a\,b$ and R than through $c\,d$ and x, consequently the needle will be deflected to one side. By increasing R this excess of current will be diminished, and the deflection of the needle also decreased, until the needle again stands at zero. Then the currents flowing through both coils of the galvanometer are equal, and therefore the resistance of both branches must be equal, viz.

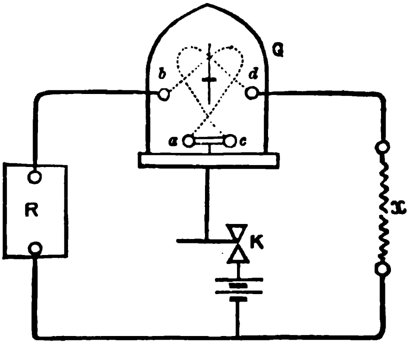
$$x + 50^{\omega} = R + 50^{\omega},$$

that is, $$x = R.$$

By further increasing R the needle would be again deflected, but in the opposite direction to that previously obtained.

Before making a test it is advisable to find out and note in which direction the needle is deflected when R is too large or too small, so that immediately the needle moves to one side or the other we may know whether it is required to increase or decrease R.

FIG. 81.

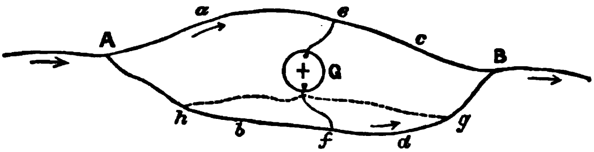


It may be necessary to measure resistances which are either higher or lower than any which can be inserted in the box R. The range can then be extended by shunting one coil of the galvanometer — say by a wire one-ninth of the resistance of the coil. Then, as only one-tenth of the current in that branch will pass through the galvanometer coil, a balance will be obtained when the total resistance in that branch is one-tenth of the resistance of the other. For instance, suppose the coil of the galvanometer connected to R to be so shunted, and a balance to be obtained, when the resistance in R amounted to 650; then the unknown resistance would be 6,500$^{\omega}$ nearly. We say nearly, because, in order to obtain a perfectly accurate result, compensating resistance must be inserted to make the resistance of the shunted galvanometer coil equal to 50$^{\omega}$, as explained in the preceding chapter.

In measuring electro-magnets or any single wound coils, a sudden jerk of the needle, due to self-induction (see Chapter VII.), will always be noticed on making and breaking the circuit. In such cases care should be taken to see that the needle rests at zero when no current is flowing, and then the key should be depressed and the adjustments made with a steady uninterrupted current until the needle again comes to zero.

The differential galvanometer, although a first-rate instrument for comparing two resistances by the equalisation method, loses in simplicity and rapidity when shunts have to be used and allowed for. By means, however, of a piece of apparatus known as the 'Wheatstone Bridge,' the value of any resistance can be readily measured. The principle of this invaluable apparatus is very simple, and is explained by the diagram (fig. 82). Let us suppose two wires, A *a c* B and A *b d* B, either equal or unequal in resistance, to be joined up in parallel and a current sent through or divided between them, as shown in the figure. The current will, as already explained, divide itself between the two wires inversely as their resistances, but, for our present purpose, the current strength is a matter of little or no importance.

FIG. 82.



If, now, one end of a galvanometer coil, G, is joined to any point, *e*, in one wire, and the other end to a point, *g*, in the other, very near to the junction B, a deflection of the galvanometer needle will be observed, indicating a current flowing from *e* to *g*.

On removing the galvanometer wire from *g* and joining it to another point, *h*, also in the second wire, but very near to A, the galvanometer will again indicate a current, but flowing in the reverse direction, viz. from *h* to *e*. If contact were successively made at points along the wire A *b d* B farther from A, the current would become feebler and feebler until, finally, a point, *f*, would be found at which the needle would not be affected at all, showing the absence of a current through the galvanometer.

There can be but one explanation to these experiments. It was clearly laid down and demonstrated in Chapter II. that whenever a current of electricity flows, it does so invariably in virtue of a difference of potential between the extremities of the conductor through which it flows, and, conversely, whenever the extremities of a conductor are at different potentials a current flows through it. These two facts must never be lost sight of, for they constitute the key to a host of electrical phenomena and problems. Inasmuch, then, as it was seen, by the evidence of the galvanometer, G, fig. 82, that a current passed through it when its terminals were connected to the points *e* and *g*, and to the points *e* and *h*, the current or currents flowed as a consequence of a difference of potential between those points. And the absence of a current on connecting the points *e* and *f* together is an equally clear proof that those two points were at the same or equal potentials. If we suppose A to be at a higher potential than B, and connect the galvanometer directly to those points, so that it shall share the current arriving at A, the needle will be deflected to one side or the other, the particular deflection being governed by the direction of the current round the needle. Let us suppose the deflection to be to the right. Then, on connecting the galvanometer to A and *g*, or even to *e* and *g*, the deflection will also be to the right, and will establish the fact that the potential at *e* is higher than that at *g*. On the other hand, the opposite deflection which is obtained when the galvanometer is connected to *e* and *h* affords ample proof that the potential at *h* is higher than that at *e*. Now, as the ends of the two wires at A are always at the same potential, and as the ends at B are also at the same potential, although lower than that at A, it follows that the fall of potential along A *a c* B must equal that along A *b d* B. It also follows that if we fix upon any one point in either of the wires, there must always be a point somewhere in the other wire which will be at exactly the same potential, and if these two points are connected together no current can possibly flow between them. Herein is the underlying principle of the Wheatstone bridge.

We must now endeavour to discover what relation, if any, exists between the resistances of the four sections into which these wires are divided. Let the resistance of the section between A and

e be denoted by a, that between A and f by b, between e and B by c, and between f and B by d.

The difference of potential between A and e is equal to that between A and f; call this P_1.

Again, the difference of potential between e and B is equal to that between f and B; call this P_2.

Now we have seen that in every case (since by Ohm's law $E = CR$) the difference of potential between any two points is equal to the current flowing, multiplied by the resistance of the conductor between those points.

Suppose the current flowing in the upper branch, A e B, to be C_1, and that in the lower branch, A f B, to be C_2.

Then
$$P_1 = C_1 \times a;$$
also
$$P_1 = C_2 \times b;$$
therefore
$$C_1 \times a = C_2 \times b,$$
or
$$\frac{a}{b} = \frac{C_2}{C_1}.$$
Again,
$$P_2 = C_1 \times c,$$
also,
$$P_2 = C_2 \times d,$$
therefore
$$C_1 \times c = C_2 \times d,$$
or
$$\frac{c}{d} = \frac{C_2}{C_1}.$$
But $\frac{a}{b}$ is likewise equal to $\frac{C_2}{C_1}$;

consequently
$$\frac{a}{b} = \frac{c}{d}.$$

This is the relation between the resistances which we sought to discover, and we might, in the same way, prove that it holds good for other cases where the resistances have different values.

The relation may also be viewed from another standpoint. The fall of potential along a conductor is proportional to its resistance, and, conversely, the resistance of a conductor is proportional to the fall of potential which takes place along it. Now, the total fall of potential along the two branches (fig. 82) is equal in amount, and the potential at e is equal to that at f; and the fall along a is equal to the fall along b, and also the fall taking place along c is equal to that along d. Therefore, the value of the resistance a bears to that of c the same ratio as does b to d, that is

$$a : c :: b : d,$$

or

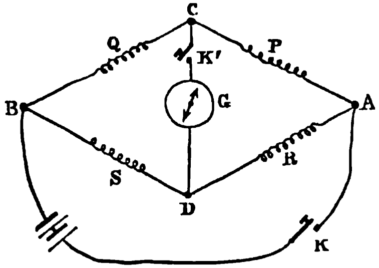
$$a : b :: c : d.$$

If one of these resistances, say c, were unknown, and the other three known, we could readily determine the value of c, for $c = \frac{ad}{b}$.

This is, in fact, the method by which resistance is measured with the Wheatstone bridge.

We have four resistances, P Q R S, one of which, say P, is unknown and the others known, and join them up as in fig. 83. The junctions at A and B are maintained at different potentials by means of a suitable battery, while to the other junctions, C and D, a galvanometer is connected. The known resistances are then varied and adjusted, until the absence of a current through the galvanometer proves C, the junction of P and Q, to be at the same potential as D the junction of R and S.

FIG. 83.



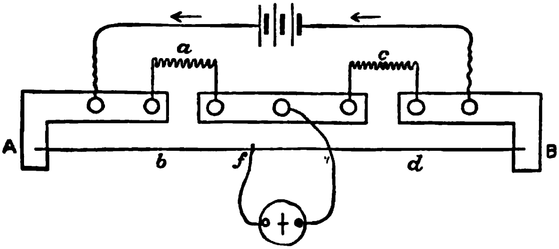
The value of P can then be calculated, as above, the simplest case being when Q = S, for then P = R. Two keys, K and K^1, are provided for the purpose of disconnecting the battery and galvanometer circuits respectively.

There are various ways of performing the necessary adjustment of the known resistances.

In the case shown in fig. 82 we found the point of equilibrium by shifting one of the wires connected to the galvanometer along A b d B, thus varying the *ratio* of the resistances b and d; and a very good form of bridge for measuring low resistances may be constructed upon this principle.

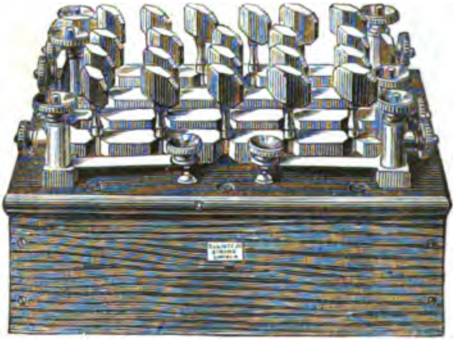
Three brass or copper strips, so stout as to have practically no resistance, are fixed on to a mahogany board, as in fig. 84. Between the ends of two of these strips a wire, A B, is stretched. It is convenient to have this wire one metre in length, with a scale placed under it, divided into a thousand parts. There are three terminal screws on the middle strip, and two on each of the others. The unknown resistance, *c*, is connected to the two adjacent ends of the middle and right-hand strips, while a known resistance, *a*, is joined to the adjacent ends of the other two. A battery is joined up to the outside strips, and a current can thus be sent through the branch *a* and *c*, and the branch *b* and *d*, in parallel. One end of the galvanometer coil is joined to the terminal screw at the junction of *a* and *c*, where the potential will have fallen to a certain amount. The other is connected to a slider which passes along over the wire *b d*, and which, when pressed down, makes contact with the wire, and allows the exact point at which contact is made to be read on the metre scale. As previously explained, a point, *f*, is sought for, at which, contact being made, no current flows through the galvanometer. Then $c = \frac{d}{b} \times a$. It is clear from this equation that $\frac{d}{b}$ is merely a ratio, and need not be known in ohms. If the wire A B is of uniform resistance throughout, it is sufficient to know the length in millimetres of *b*, and the length in millimetres of *d*; but the resistance of *a* must be known in ohms. Supposing *a* were 2·5 ohms, and a balance to be obtained with the slider at a point 440 millimetres from A; then $b = 440$, and $d = 560$. Therefore $c = \frac{560}{440} \times 2{\cdot}5$ $= 3{\cdot}1\dot{8}$ ohms.

FIG. 84.



The stretched wire must be of considerable resistance so as to make the fall of potential per unit of length appreciable, and it should be of some hard durable metal, otherwise it would become worn by the slider and its uniformity of resistance destroyed. For these reasons the wire should be made of German silver, platinum silver, or platinoid. A key should be inserted in the battery circuit, to prevent the current being kept on longer than necessary, and heating the wires. Extra resistance in the galvanometer or battery circuits introduces no error, merely reducing the sensitiveness of the arrangement. But it is important to secure good clean connections in the other branches, as any resistance introduced there might cause a great error in the result. To obtain the best results the resistance of the battery should be low and its E.M.F. high; the resistances in the arms of the bridge should not differ very greatly, and the galvanometer must, of course, be sufficiently delicate to indicate the difference of potential caused by moving the slider through the shortest measurable distance. But the length of the wire on the galvanometer must not be indefinitely increased to attain this result, otherwise the resistance so added reduces the current in a greater proportion than the deflective effect is increased.

FIG. 85.

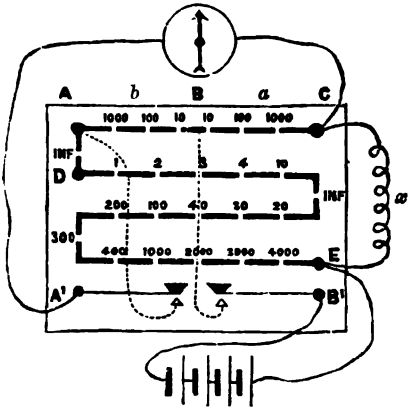


There is, in fact, for every separate test, a certain resistance which it would be best to give the galvanometer. In practice, however, we can do no more than wind the galvanometer in such a manner as will make it best suited to the average conditions under which it will be employed. For an ordinary slide-wire bridge the galvanometer resistance should not greatly exceed one ohm.

The slide-wire bridge answers well in a laboratory, and is exceedingly valuable for measuring low resistances. A more practical form of the Wheatstone bridge and one which is very largely used for general work is shown in fig. 85, and its connections in fig. 86.

There is no exposed stretched wire here, but all the resistances are placed in a mahogany box with an ebonite top, their ends being connected to brass blocks fitted with plugs as in the case of any ordinary resistance-box. These resistance coils are measured with extreme care, and the value of each in ohms is marked (often indistinctly, by the way) upon the ebonite. Double terminal screws are employed to avoid risk of resistance being introduced by the careless connection of two wires on to one terminal. In the general view it will be seen that there are two keys, each, when depressed, making contact with a metal stud; these keys are marked A′ B′ in fig. 86. A terminal screw is connected to each key, and to the right-hand one is joined the zinc pole of the testing battery. The stud under this key is connected beneath the ebonite cover to the brass block B in the middle of the back row of resistances, so that the zinc pole of the battery is joined to this block when the right-hand key is depressed. It is at this point then, corresponding to B, the junction of Q and S in fig. 83, that the current divides, and on either side are three coils of 10, 100, and 1,000 ohms respectively, any or all of which can be inserted at pleasure. At each end of this row of coils is a terminal screw, and the galvanometer is joined up to these points. But, as we have seen, it is necessary to have a key in the galvanometer circuit, and i is very convenient to place both keys close together, as shown. One wire from the galvanometer is therefore brought to terminal

FIG. 86.



A′—that is, to the left-hand key—and the stud under this key is connected to terminal A, as shown by the dotted line. Therefore, when A′ is depressed, this side of the galvanometer is joined to terminal A. The other side of the galvanometer goes direct to terminal C. The two 'arms' of the bridge, B A and B C, correspond to S and Q in fig. 83, and the arm marked R in that figure here consists of a number of coils, ranging from 1 ohm to 4,000 ohms, placed between the terminals D and E. We have thus three arms of the bridge of known values, and the fourth, or unknown resistance, x, is placed between terminals C and E. The copper pole of the battery is brought direct to terminal E, which corresponds to the junction of P and R in fig. 83. Between the arms B A and D E—that is, between the terminals B and D—is a space marked 'infinity.' There is no coil connected to the two blocks at this point, so that the resistance is infinite, that is, the circuit is disconnected when the plug is removed. This arrangement is exceedingly useful, for it is possible to increase the range of measurement considerably, by removing the plug and inserting an extra box of coils in the circuit here; and further, it is often convenient, in some tests, to be able to separate the coils into two independent sets. There is a second 'infinity plug' between the 10 and 20 ohm coils, and when using the apparatus simply as a set of resistance coils these plugs may be used as keys for disconnecting or joining up the circuit.

Now, suppose the bridge to be properly joined up, with an unknown resistance x, the value of which it is desired to find, between C and E.

It is clear that A and C are the points which we want, by adjusting the various resistances, to bring to the same potential, and the galvanometer is connected to these points so as to indicate when this result is attained. We begin by inserting some resistance in the arms B A and B C, say 100 ohms in each. These resistances are not again altered during the measurement, but the adjustment is made by varying the amount of resistance in the arm D E until the galvanometer shows that a balance has been obtained. When this happens the value of the unknown resistance, x, is equal to the amount which has been inserted in the arm D E. Much time may be saved and greater accuracy ensured by taking a test methodically, and the following points should be attended to. Before starting it should be ascertained that the plugs are firmly in their places and that all the connections at the terminals are good, and to ensure this it is advisable to take advantage of the double terminals provided, and place only one wire on each screw. The galvanometer having been placed in a position convenient for the experimenter, some coils in each of the three arms must be put into circuit, the amount in the arms D E being made as near the unknown resistance as can be guessed. The right-hand key should be depressed and then, a moment afterwards, the left-hand key, and the galvanometer observed; probably the latter will indicate the passage of a current, and it should always be found which way the needle moves when the resistance in the arm D E is, say, too high. If that is done, one can see, immediately the needle moves, whether it is necessary to increase or reduce the resistance in D E in order to get a balance. This is much quicker than obtaining the balance at random. The galvanometer key must only be lightly tapped so as to just indicate in which direction the resistance must be varied, until a balance is nearly obtained, when it may be held down for a longer period. This prevents a heavy current being passed through the galvanometer; and the student will hardly require warning that if the battery is kept on too long the coils will become more or less heated and their resistance varied. It should also be borne in mind that with a very delicately made instrument a suddenly applied heavy current is likely to injure the needle or the pivot.

We considered above the simple case when the resistances of the arms B A, B C were equal, but the bridge is not always used under these conditions.

If, for instance, the unknown resistance is comparatively low and we desire to measure it to within a fraction of an ohm, it is then necessary to have these arms of unequal resistance; we should, in fact, make B A 100 ohms and B C 10 ohms. Then, if a balance were obtained with 13 ohms in D E, x would be equal to 1·3 ohms. For, by the principle of the bridge,

$$x = \frac{\mathrm{BC} \times \mathrm{DE}}{\mathrm{BA}} = \frac{10 \times 13}{100} = 1{\cdot}3.$$

And by using 1,000 ohms in B A and 10 in B C, measurements to within $\frac{1}{100}$ of an ohm might be made.

When the unknown resistance is very high, then the ratio must be reversed, taking, say, 10 in B A, and 1,000 in B C. If, now, a balance is obtained with 1,309 ohms in D E, then

$$x = \frac{1000}{10} \times 1309 = 130900 \text{ ohms.}$$

When using this ratio it is not always possible to obtain a perfect balance and so determine the unknown resistance exactly, because the lowest unit in the arm D E is 1 ohm, and this is equivalent to 100 ohms in the unknown resistance. For instance, if in the last test the unknown resistance were 130,925 ohms, it would be necessary to increase the resistance in D E by a quarter of an ohm in order to get a perfect balance, and this fraction is not at our disposal. A supplementary set of resistances having fractional values may be inserted between the terminals A and D, provided that the arrangement is sufficiently sensitive for the galvanometer to respond to the change produced by these fractions of an ohm; but for general work it is sufficient to know the value of a very high resistance to within 10 or 20 ohms, and this can always be estimated by observing the movements of the needle when the resistance in D E is less than 1 ohm too high and less than 1 ohm too low.

It may be remarked that the efficiency of the Wheatstone bridge is reduced by the injudicious choice of a battery, more frequently than by any other cause.

The point to be borne in mind is, that a considerable fall of potential is necessary along the arms of the bridge, that is, between the points A and B in fig. 82. The greater the difference of potential between these points, the greater will be the effect on the galvanometer needle for a given change in any of the resistances, and therefore the higher the degree of accuracy to which we can measure. Now, suppose the bridge to be of the slide-wire form, and the resistance of the arms between A and B to be 2 ohms. If we employ a battery of 10 Daniell cells, having a resistance of 5 ohms per cell, the potential difference between A and B will be considerably less than three-quarters of a volt, all the rest of the fall taking place inside the battery. A single Grove cell, having a resistance of $\cdot 2^{\omega}$, could maintain about 1·8 volts under similar conditions, although its E.M.F. is only one-fifth of that of the Daniell battery. This clearly shows the evil effect of resistance in the battery, and it is evident that when the resistances in the bridge are low, the battery employed, while having a sufficiently high E.M.F., *must* have a very low internal resistance. When, however, the resistances are high, resistance in the battery circuit is not so harmful (as the fall of potential in any part of a circuit is directly proportional to the resistance of that part), and a battery of Daniell cells may be employed. The E.M.F. of the battery is often kept unnecessarily low to avoid a strong current heating the coils; there is, of course, a limit, but by a skilful manipulation of the keys provided, the time during which the current need be kept on is so very short that the heating is inappreciable. We have remarked that it is better to depress the battery key first, and allow the current to become steady before tapping the left-hand key and throwing the galvanometer in circuit. A very short time is sufficient for this, but extra care should be taken that it is done when the unknown resistance is an electro-magnet, or any coil which is liable to the phenomenon of 'self-induction' (see Chapter VII.), or when it has any 'electrostatic capacity,'[1] as in the case of a telegraph line or cable, otherwise the needle will move violently, although the actual resistance may be truly balanced. To enable the student to understand how the nature of the resistance can cause the potential at any two points to be widely different when the current is starting or stopping, and yet equal when it is steady, we may employ an analogy. Suppose we have two equal iron water-pipes joined up as in fig. 82, with some piece of apparatus to indicate a difference or equality of pressure, in the place of the galvanometer, the points *e* and *f* being at equal distances from A or B. Then, the pipes being equal in all respects, the pressure at *e* and *f* will always be equal, no matter how the difference of pressure at A and B may be varied. If, now, one branch, A *f* B, is replaced by a very flexible india-rubber pipe of similar dimensions, this no longer holds good. Suppose the pipes to be empty and then water at a high pressure to be forced in at A; the pressure at *e* will rise quicker than at *f* because the flexible pipe expands, and this occupies a short time. When the expansion has reached its limit the pressures at *e* and *f* are equal, but on suddenly stopping the flow at A, the pressure at *f* becomes higher than at *e* for a brief moment owing to the contraction of the pipe.

---

[1] The scope of this work will not permit us to deal with this branch of the subject; 'electrostatic induction' has seldom to be contended with by the electric-light engineer.

Somewhat similarly, as we shall see later on, a current of electricity can never rise to its full value, or die away instantaneously; for this reason, the coils of the bridge are so wound that in them the rise or fall is very rapid, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady before the second key is closed.

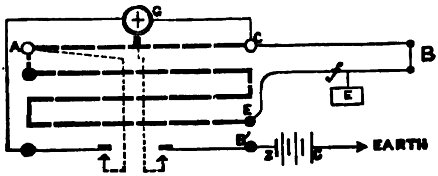
The peculiar method of winding the bridge coils is also useful in preventing any direct action, which might be caused by the current circulating in them, being produced upon the galvanometer needle. When an electro-magnet is being measured, the galvanometer must be placed far enough away to avoid its being affected when the current is passed through the electro-magnet. When there is any reason to suppose that some such effect as this exists, the battery key should be closed and opened several times, the galvanometer key being left open and the needle watched. If it moves at all, we have proof positive that some portion of the apparatus is producing a disturbing effect upon the galvanometer.

We will describe one other test, known as the 'Loop test,' which is rather interesting, and may prove useful to an electric-light engineer.

When both ends of the unknown resistance are not easily accessible, it may be measured by joining one end to the terminal C, and connecting the distant end to earth. The terminal E—that is, the junction of the arm D E—and the copper pole of the battery are also put to earth, and then the test can be made in the usual manner, because the two earth-connected points are at the same potential, and behave in precisely the same way that they would if they were joined to a common terminal. A leakage sometimes occurs in a covered wire or cable, which allows more r less of the current to escape to earth, provided some other point of the system is also earthed. It is necessary to determine the distance of such a 'fault,' or point of leakage, and it might easily be done by disconnecting the line beyond it, and then, treating the fault as an earth, measuring the resistance of the wire up to this earth as described above.

It rarely happens, however, that any fault develops which does not offer considerable resistance to the passage of the current to earth, and as the amount of this resistance is never known it cannot be allowed for. Further, the resistance frequently varies so rapidly that it is not possible to obtain a balance at all, and some different arrangement of the bridge is necessary. We have seen that in the battery circuit extra resistance, and even variable resistance, causes no error in the result, although it reduces the sensitiveness of the bridge; and if this variable earth fault can be placed in the battery circuit, we can ignore its resistance altogether. This can readily be done if both ends of the wire are accessible; if not, it is necessary to have a second or return wire, and connect the distant ends of the two together. This arrangement is shown in fig. 87. The copper pole of the battery is put to earth, the zinc pole being always joined to line in fault-testing, as the current in that direction—usually by an electrolytic effect—decreases the resistance of the fault. E B is the faulty wire, the fault being shown at *f*. C B is the sound wire by means of which we reach the other end of the faulty wire, the two being looped together at B. The good wire is joined to terminal C, and the faulty one to E. On depressing the battery key the current flows through the bridge and the lines, finding earth at the fault, and a balance can be obtained in the usual way. Let R be the resistance inserted in A E, and let x represent the unknown resistance of the faulty wire from E to the fault at *f*. Then the total resistance of this arm of the bridge is R $+ x$. The other arm consists of the sound wire, C B, and that portion of the faulty

FIG. 87.



wire from B to *f*. Let the total resistance of this arm be called *y*. Let *a* be the resistance in B C, and *b* that in B A, then

$$a : y :: b : \text{R}+x,$$

that is,

$$y = \frac{a}{b} \times (\text{R}+x) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

We have here two unknown quantities, *x* and *y*, and must therefore get a second simple equation in order to eliminate one of them. It is clear that the total resistance of the two lines is $x+y$, and usually this is known; if not, it can be measured by joining up the bridge in the ordinary way (that is, connecting the copper pole of the battery to terminal E), and measuring the resistance of the loop as if no fault existed; for there will then be no leakage at the fault, as no other part of the system is earthed. Suppose the resistance thus found to be L ohms, then

$$x+y = \text{L};$$

therefore

$$y = \text{L}-x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Therefore, from equation (1),

$$\frac{a}{b} \times (\text{R}+x) = \text{L}-x;$$

therefore

$$x = \frac{b\,\text{L}-a\,\text{R}}{a+b}.$$

If we make $a = b$, as is frequently done in this test, then, evidently,

$$\text{R}+x = \text{L}-x,$$

and

$$x = \frac{\text{L}-\text{R}}{2};$$

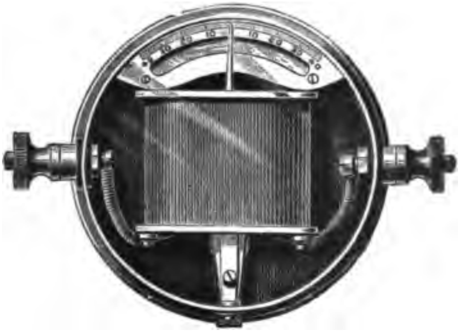
or, we simply subtract the resistance in A E from that of the two lines, and, dividing by 2, obtain the value of *x*.

Now, *x* is the resistance in ohms from E to the fault; the length of the wire E B is known, and therefore its resistance per mile, or any other unit of length, is known. Thus we can at once ascertain the distance of the fault in miles or yards by dividing *x* by the resistance per mile or per yard.

The galvanometer used with the form of bridge above described has a resistance of 800 ohms; it is shown in fig. 88, and is a very good instrument—portable, yet capable of giving evidence of a very small potential difference. When joined up in circuit with a resistance of 20,000 ohms, and a single Daniell cell (the current then being about one twenty-thousandth of an ampere), it will give a deflection of 25°.

The coil consists of many turns of fine silk-covered wire, wound on a single brass bobbin. The needle, which is pivoted, lies exactly in the centre of the coil, and is quite covered by it. At right angles to the needle is fixed a pointer, which projects from the coil, and, passing over a scale and a strip of looking-glass, indicates the slightest movement of the needle. A lever is provided for lifting the needle from its pivot when not in use, and each end of the coil is connected to a terminal which is insulated from the brass casing by ebonite. The features in the design of the instrument which enable it to respond to very feeble currents are the great length of wire employed, the nearness of this wire to the needle, and the excellent pivoting of the needle, which allows it to move easily.

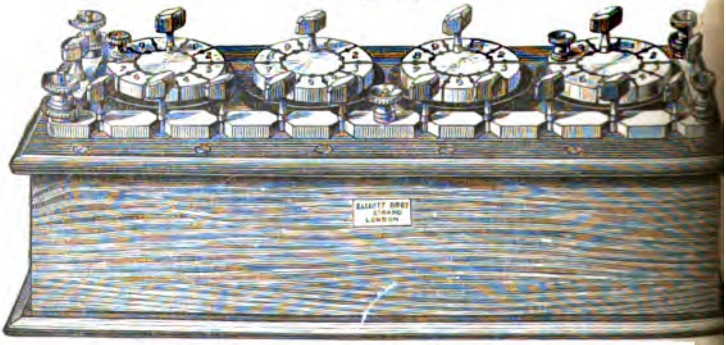
FIG. 88.



Another form of Wheatstone bridge is shown in fig. 89. This has a very great range, and some of its coils are joined up differently to those in the apparatus last described.

The two 'ratio arms' each consist of five coils, of 1, 10, 100, 1,000, and 10,000 ohms resistance, and are connected up in the usual manner. The arm which is varied in balancing is divided into four sets of coils, each set consisting of nine *equal* coils. The resistance of each coil in the first set is 1^{ω}, in the second 10^{ω}, in the third 100^{ω}, and in the fourth $1{,}000^{\omega}$. Sometimes a fifth set of $\cdot 1^{\omega}$ each is added. In the figure will be seen 10 brass blocks surrounding a circular central one, with which they can be separately connected by a plug. The block partly hidden by the plug is numbered 0, and this block is connected to the centre of the next dial. Between each of these numbered blocks (except 9 and 0) one of the equal resistance coils is placed, and by means of the plug any number of them can be brought into circuit. For instance, if the block numbered 5 is so joined to the centre plate, the current passes from the plate by means of the plug, and through five of the coils round to the block number 0, which is joined to the next centre plate, or, in the case of the last dial, to a terminal screw. Some tests can be very quickly made with this form of bridge, and the result seen at a glance. Of course, the circuit is disconnected in the variable arm every time a plug is shifted, if only one plug is used for each dial.

FIG. 89.

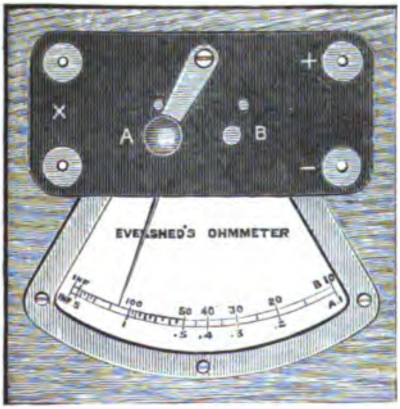


One of the most important uses to which the instruments and methods described in this chapter can be applied, is that of determining the 'insulation resistance' of an electrical circuit, which is accomplished by entirely disconnecting the remote ends of the conductors, and then measuring the resistance offered by the insulating material to the leakage of a current from one conductor to another, or to earth. Should this resistance fall below a certain prearranged standard, evidence will be afforded of the existence of a fault which requires to be localised and removed forthwith. The insulation of the conductors having been proved, the switches and other fittings may then be joined up, when a second careful test should be made, which in most cases will reveal the fact that the insulation resistance has fallen considerably, often as much as 50 per cent., due mainly to surface leakage. By testing the insulation resistance of the conductors separately, a ready means is afforded of determining whether a particular fault is in the covering of the wire, or in the fittings, and it may be observed that a certain amount of leakage at the fittings should be deemed of less importance than an equal or even a smaller leakage in the conductor covering; for whereas in the former case it is mostly due to moisture and therefore not liable to any serious increase, in the latter case it indicates a damaged or inferior insulating material, a fault which will most assuredly develop under the continued electrical stress.

In electric light installations very heavy currents and rather high E.M.F's. are frequently employed, which might cause serious damage to life and property should the insulation at any point be allowed to fall below a certain standard or become in any way faulty, and any such fault would, of course, also impair the efficiency of the lighting, to say nothing of the energy wasted. Similar conditions obtain with any system of electrical conductors and fittings for any purpose whatever, and it is necessary that some convenient means should be available for efficiently testing the whole installation, under conditions equally trying to the maximum stress which it will be called upon to sustain in practice. Especially must the source of electrical power employed for the test be able to develop an E.M.F. at least equal to the maximum intended to be used, otherwise there will be considerable risk that small incipient faults will not be shown up during the test, and will only become manifest when the circuit is in practical use, and when, therefore, the greatest inconvenience, and possibly damage also, will result.

As 100 volts is the lowest E.M.F. which generally obtains in practice, it is evident that the employment of batteries for testing would be exceedingly inconvenient, so much so, in fact that an efficient test is frequently shirked. A small magneto machine, such as we shall describe in a subsequent chapter, is far more convenient and portable, but it is hardly suitable for use with the apparatus ordinarily constructed for the measurement of resistance. Within the last few months an instrument has been introduced by Messrs. Goolden which answers admirably, and, in fact, is designed to work with such a machine. It is called an 'ohmmeter,' from the fact that its pointer indicates directly the number of ohms in the resistance under measurement. In practice, however, one does not actually require to find the exact resistance of an installation within a few ohms more or less. It is, indeed, sufficient if the apparatus can assure us whether, under the stress produced by a sufficiently high E.M.F., the insulation is above or below the standard, which we may here suppose to be fixed at 1 megohm (a million ohms). If below this standard, the circuit should be tested in sections until the fault is localised. The apparatus in question can promptly and decidedly indicate whether a resistance is above one megohm or below it, and supposing it to be above, of course the installation is passed as satisfactory. A top view of the instrument is given in fig. 90. When the small switch is placed as shown on the contact A, the outer scale A is to be used, but by shifting the switch to the contact B, a coil is shunted, thus enabling the lower resistances to be measured by readings on the inner scale, B. The wires from the source of E.M.F. (the magneto machine) are attached to the terminals marked + and —, while wires leading from the resistance to be measured are attached to the other terminals marked ×.

FIG. 90.



It is not possible to measure the higher resistances with certainty to within 100 ohms or so, but this is immaterial, as, if the insulation is below the standard, it matters little whether it is 700,000 or 700,200 ohms.

Fig. 91 is a view of the interior of the instrument turned upside down, the working parts there shown being placed under the ebonite slab on which the switch and terminals are fixed.

The scale plate is shown in fig. 90. The inner of the two scales is marked in divisions of 1,000 ohms from ten thousand up to infinity, while the outer reads in megohms from 0·1 megohm to infinity, the scale being fairly open up to 5 megohms. In the construction of the instrument there are three coils (shown in plan in fig. 92); two of them, *a a*, are placed with their planes parallel and are joined in series, while the third, *b*, is placed between and with its plane and magnetic axis at right angles to those of the coils *a a*. The inner coil, *b*, is shaped so as to allow the pointer to travel through a comparatively wide range. The figure, which is drawn from the under side, also shows the small steel needle in its zero position. This needle is then lying in the centre of the coil *b*, and along the common axis of the coils *a a*. In the case underneath it is placed a small weak bar magnet which adjusts itself so as always to neutralise the effect of the earth's magnetism, and, consequently, the only magnetic forces acting upon the needle are those due to the currents in the coils. A current passing through the coils *a a*, which are of high resistance, tends to keep the magnetic needle in the position shown, that is, at zero, with its length along the common axis of the coils *a a*. But its length is then parallel to the plane of the coil *b*, and any current

FIG. 91.

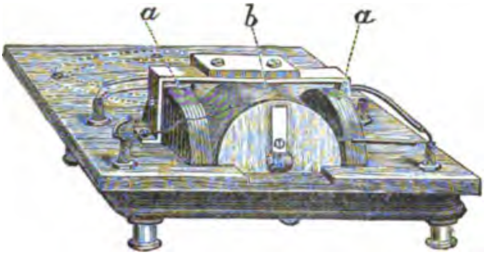
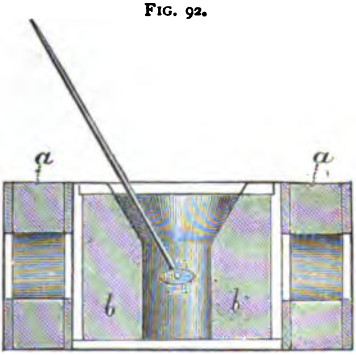


FIG. 92.



passing through this coil will deflect the needle more or less,
position of rest depending upon the relative strength of the curren
in the magnetising coils and the deflecting coil. Now the co
a a are connected to the source of E.M.F. only, consequently th
current in them, and the force with which the needle is urged t
the zero position, is directly proportional to this E.M.F. The coil
is connected to the same source of E.M.F. but has the resistance t
be measured joined in series with it; this resistance is very hig
and the current through *b* which tends to deflect the needle i
inversely proportional to it. The deflection of the needle a
indicated by the pointer is proportional to the E.M.F. and
versely proportional to the resistance; but as the same source
electro-motive force is used for both branches of the cir
any variation affects equally the deflecting and the magneti
currents, and, therefore, the deflection of the needle is sim
inversely proportional to the resistance to be measured, that of
coil *b* being small.

When the resistance is infinite no current flows through
deflecting coil and the needle remains at zero, but as the
sistance is lowered the deflection of the needle is proporti
increased, and it becomes a simple matter to calibrate the
ment so that the pointer shall indicate directly the value
resistance in ohms or megohms. The ohmmeter, and the ac
panying magneto machine which develops an E.M.F. of 120
are enclosed each in a case of 5 inches cube, affording a
compact set for testing at the highest working pressure like
be adopted in an ordinary installation.

CHAPTER VI.

MEASUREMENT OF ELECTRO-MOTIVE FORCE.

In all classes of electrical work it is important to be able to accurately measure potential difference, or electro-motive force, and no better introduction to this branch of the subject can be obtained than that furnished by the study of the methods by which the electro-motive force of batteries can be compared. By Ohm's law we know that $E = C\,R$, where R is the total resistance of any circuit measured in ohms, C the current in amperes flowing through it, and E the electro-motive force in volts which maintains that current. So that, whenever the resistance and the current strength are known, the E.M.F. can be ascertained by multiplying these two quantities together. For instance, if a battery having a resistance of 15 ohms is joined up to send a current through a galvanometer of 320 ohms resistance, with a rheostat having 960 ohms unplugged, also in circuit, and if the resulting current is found to be 8 milliamperes, then the electro-motive force of that battery is $C \times R$ or $\cdot 008 \times 1295 = 10\cdot 36$ volts.

The measurement of current strength presents but little difficulty, but it is not often that the total resistance in the circuit is accurately known without measurement, and thus two tests at least are rendered necessary in order to ascertain the E.M.F. In practice it is usual to take some good constant cell or battery whose E.M.F. is known exactly and compare the unknown electro-motive forces with that of this 'Standard' cell or battery. As the accuracy of the results depends upon the accuracy of the value which is given to the E.M.F. of this standard, and upon its constancy, great care must be exercised in the choice and use of such a cell.

The best cell for a standard is that devised by Latimer Clark, which was described in Chapter III. If carefully used it will remain constant for years; but, as it polarises quickly, it should not be allowed to send so strong a current as even 1 milliampere, and, if possible, should only be used in those tests, to be presently described, in which the batteries are tested when they are not sending any current at all, but simply maintaining a potential difference. A rather serious drawback to this cell is, that its E.M.F. varies with a change of temperature, falling as the temperature rises; and although, the temperature being known, the variation of E.M.F. can be allowed for, such calculations are very inconvenient and take time. Its E.M.F. at 15° Centigrade is 1·435 volts.

The Daniell cell when in good condition does not polarise, even when developing a strong current, and it has the further advantage that a considerable variation of temperature make little or no difference in its E.M.F. It is, therefore, a goo standard for use in the workshop, and any form of Danie cell in first-rate order may be employed, especially when t tests are independent of the battery resistance. But it mu be remembered that the plates should be bright and clean, t supply of crystals in the copper cell plentiful, and the solutio the zinc cell half saturated. The E.M.F. then is 1·079 volts.

Since the current which a battery can develop is proportio to its E.M.F., it is evident that the E.M.F. of two batteries can compared by observing the currents which they send throu circuits offering *equal* resistances. The Daniell cell should used as the standard in this case, and if it gives on a tange galvanometer 25 divisions deflection through a total resistance say, 1,000ω, while another cell or battery gives 62·5 divisio through the same resistance, then

$$25 : 62\cdot5 :: E : x,$$

where E is the E.M.F. of the standard cell, and x that of t battery under measurement.

Therefore $$x = \frac{62\cdot5 \times 1\cdot079}{25} = 2\cdot7 \text{ volts nearly.}$$

One objection to this method is, that it is necessary to kno the resistance of the batteries, in order that the total resistan may be made the same in both cases; but if the resistance of the external circuit is comparatively high, then the resistance of the batteries may be ignored.

In this simple method, the resistance is kept constant, while the current varies. The various currents are then measured and the relative E.M.F. deduced therefrom.

But it is also possible to compare electro-motive forces by varying the resistance and keeping the current constant, in which case the electro-motive force is proportional to the resistance; for, the higher the E.M.F., the greater is the resistance through which it can send a given current. One great advantage in connection with this method is, that any kind of galvanometer which may be available can be employed, because the same deflection is produced in every case. In order, therefore, to compare the E.M.F. of any battery x, with the standard cell E, we should join up the standard cell in circuit with a rheostat and galvanometer, varying the resistance so as to obtain a convenient deflection of, say, 45°, and noting carefully the total resistance, R_1, in circuit. The battery to be tested should next be joined up, and the resistance altered, say, to R_2, so as to reproduce the deflection of 45°.

Then $$x : E :: R_2 : R_1 \text{ or } x = \frac{E\,R_2}{R_1}.$$

In this test, too, the resistances of the standard cell, the battery, and the galvanometer must be known and taken into account unless the resistance in the rheostat is comparatively high, when these other resistances may be ignored.

But by a simple extension of this method, it is possible to obtain an accurate result without knowing either of these three resistances. The process consists in first joining up the standard cell, E, in the same manner as in the previous test, and then adjusting the rheostat until a deflection of, say, 45° is obtained. The resistance should then be increased until the deflection falls to, say, 35°, noting carefully the exact number of ohms, P, by which the resistance is increased, in order to bring about the reduction in the deflection. The battery, whose electro-motive force, x, it is desired to measure, must now be substituted for the standard cell, and the resistance again adjusted until the deflection of 45° is reproduced. This resistance should then be increased by, say, Q ohms until the deflection is once more 35°. Then, a shown below,

$$x : E :: Q : P, \text{ or } x = E\frac{Q}{P} \text{ volts.}$$

To take an example. If with the Daniell cell as a standard the insertion of 720 ohms reduces the deflection 10°, that is to say, from 45° to 35°, and when the battery is substituted it is found necessary to add 2,300 ohms to reduce the deflection through the same 10°, then

$$x = 1{\cdot}079 \times \frac{2300}{720} = 3{\cdot}446 \text{ volts nearly.}$$

This is a very good method, and it is interesting and instructive to observe how the battery and galvanometer resistances a eliminated. This may be shown by Ohm's law as follows:—

Let G be the resistance of the galvanometer, r_1 the inter resistance of the standard cell, and R_1 the resistance in the rhe stat when the needle is deflected through 45° by the current wh strength is indicated by C_1, then

$$C_1 = \frac{E}{R_1 + r_1 + G}.$$

Also let r_2 be the resistance of the battery whose E.M.F. is to deduced, and R_2 the resistance in the rheostat necessary to rep duce the deflection of 45°, or when the current strength can ag be indicated by C_1, then

$$C_1 = \frac{x}{R_2 + r_2 + G},$$

therefore

$$\frac{E}{R_1 + r_1 + G} = \frac{x}{R_2 + r_2 + G}$$

$$E(R_2 + r_2 + G) = x(R_1 + r_1 + G) \quad . \quad . \quad . \quad . \quad (1$$

When the resistances R_1 and R_2 are increased by P and Q respe tively to obtain the deflection of 35° which will correspond to current strength which can be called C_2, then

$$C_2 = \frac{E}{R_1 + r_1 + G + P} = \frac{x}{R_2 + r_2 + G + Q},$$

therefore $E(R_2 + r_2 + G) + EQ = x(R_1 + r_1 + G) + xP. \quad (2$

Subtracting equation (1) from (2) we get

$$\mathrm{E\,Q} = x\,\mathrm{P},$$

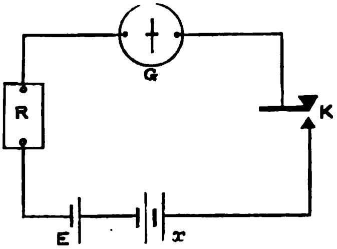
therefore

$$x = \mathrm{E}\,\frac{\mathrm{Q}}{\mathrm{P}}.$$

To ensure accurate results it is essential that the galvanometer for this test should be sufficiently sensitive to indicate a very slight alteration in the current strength, and, if possible, the resistances P and Q should be as high as or even higher than the total resistance in the circuit prior to their insertion.

There is another good method which is sometimes very convenient because it is not necessary to know or ascertain the actual resistance of any portion of the apparatus, whether it be the galvanometer, the rheostat, or the battery, these being the appliances required for the test. As in the previous tests, we may denote the E.M.F. of the standard cell by E, and that of the battery to be measured by x. The standard cell E and battery x are joined up in series, so that they assist each other in sending a current through a rheostat or set of resistance coils, R, and a tangent galvanometer, G (fig. 93), and the resistance adjusted until a fairly high deflection, say, sixty-five tangent divisions, is obtained. Then, on reversing the standard cell (supposing it to be of lower E.M.F. than x) so that the two E.M.F.'s, x and E, are opposed to each other, the resulting current will manifestly be due to the *difference* between the two E.M.F.'s, and, as the total resistance remains unaltered, the current and the deflection produced by it will be diminished, say, to twenty-five divisions. Then, denoting the first deflection (sixty-five divisions) due to both E.M.F.'s by D, and the second deflection (twenty-five divisions), due to the *difference* between the two E.M.F.'s when opposed, by d,

FIG. 93.



$$x : \mathrm{E} :: \mathrm{D} + d : \mathrm{D} - d,$$

or

$$x = \mathrm{E}\,\frac{\mathrm{D} + d}{\mathrm{D} - d}$$

Inserting the values as above, we get

$$x = 1{\cdot}079 \times \frac{65 + 25}{65 - 25} = 2{\cdot}428 \text{ volts nearly.}$$

The object of reversing the battery or cell of lower E.M.F. is to obtain both deflections on the same side of the zero point. Were the battery of higher E.M.F. to be reversed, it would cause the needle to be deflected to the opposite side of the zero, and if the pointer happened to be bent it would cause an incorrect calculation.

If, when joined up in opposition, no deflection is obtained, then the electro-motive force of the standard cell will be the same as that of the battery under test, or E = x. The only objection to the method is that in the first case the weaker battery, which is usually the standard cell, has a rather strong current flowing through it which may lower its E.M.F., while, when joined i opposition, the current is passing in the opposite direction a will almost certainly cause a slight increase in its E.M.F. In ord to eliminate as much as possible this source of error, it is advisab to introduce a 'key' or contact-maker to open and close t circuit at will, as shown in fig. 93. By the skilful manipulation this key the needle can be brought to rest immediately without single oscillation, and the deflection then read before any apprecia alteration of the E.M.F. can take place. As a further precautio the resistance in circuit should be made as high as possible so to reduce the strength of the current. By such means the obj tion becomes almost entirely obviated. To admit of high resi ance being placed in the circuit, the 320^{ω} coil of the galvanome should be used unshunted, and the magnet placed rather lo down with its north pole pointing northwards, so that it will act opposition to the earth's magnetism.

That the resistance of batteries and galvanometer need not known or ascertained is evident from the fact that they form p of the constant total resistance, which is the same in each case a which does not enter into the calculation. This may be sho algebraically, for if we let R indicate the total resistance in circ (including batteries and galvanometer), C_1 the current in the fir ase giving deflection D, and C_2, the weaker current, giving leflection *d*, then

$$C_1 = \frac{x + E}{R}, \text{ or } R = \frac{x + E}{C_1},$$

and

$$C_2 = \frac{x - E}{R}, \text{ or } R = \frac{x - E}{C_2}.$$

Therefore $\frac{x \times E}{C_1} = \frac{x - E}{C_2}$, or, since the currents are proportional to the deflections in tangent divisions, $\frac{x + E}{D} = \frac{x - E}{d}$.

Whence

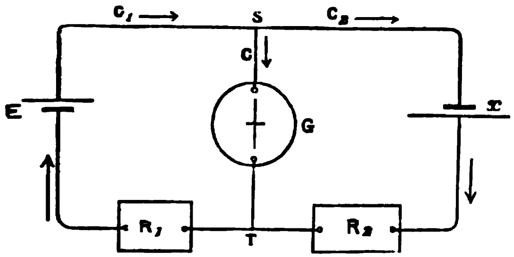
$$Dx - DE = dx + dE,$$
$$x(D - d) = E(D + d),$$
$$x = E\frac{D + d}{D - d}.$$

It will doubtless be remembered that, if the poles of a battery are joined by a short piece of thick wire having practically no resistance, the current flowing through the circuit will depend simply upon the E.M.F. of the battery and its internal resistance. Now, the thick wire coils of the tangent galvanometer which we have described are of very low resistance, and may be used for the measurement of the current which a battery can give under these conditions. Thus, supposing a battery of twenty Daniell cells, having a resistance of 5 ohms per cell, were joined up to send a current through one of the low resistance coils of the tangent galvanometer, the current flowing would be $\frac{20 \times 1{\cdot}079}{20 \times 5} = {\cdot}2158$ of an ampere, and the current from one cell, or 100 similar cells, should be the same, because when the E.M.F. is increased by increasing the number of cells, the internal resistance—that is, the total resistance in circuit—is increased in the same proportion. A galvanometer with a very low resistance coil affords, therefore, a means of rapidly testing the *condition* of a number of similar batteries, for the deflection of the needle will be decreased if either the internal resistance of any cell is above or the E.M.F. of any cell below the standard. It is, then, only necessary to ascertain the deflection given by a cell or a battery known to be in good condition, and adopt this as the standard. Then if a battery, say, of ten cells gives a current equal to that of the standard cell, may be fairly concluded that the battery is in good condition, if a second similar battery gives a deflection of seven or eig degrees less, then the conclusion is that there is something wro with it; its resistance is too high or its E.M.F. too low. The mat may be quickly decided by joining up the faulty battery in opp sition with the similar battery known to be good—that is to sa joining their copper or positive poles together and their zinc negative poles to the galvanometer. If they then give no defle tion, we know that their electro-motive forces are equal, and fault is proved to be one of high resistance. If, on the oth hand, a current is produced, there must be a difference in E.M. and the fact that the suspected battery is the faulty one would demonstrated if the direction of deflection were such as to pro that the other is urging a current through it.

But galvanometers with short thick wire coils having but few convolutions are only affected by very powerful currents, are only used where it is essential that the introduction of instrument into any circuit should have no appreciable effect the strength of the current flowing through it. When this striction is not imposed increased accuracy can usually be obt by employing a more delicate instrument, in which a coil of turns, and generally of fine wire offering a high resistance, is ployed; because, although the current through the galvanom is weakened by the added resistance, the effect is more balanced by the increased number of times which the cur travels round the needle. In fact, the flow of a very fe current through such an instrument, or the maintenance of a low difference of potential at its terminals, may suffice to pro a good deflection, while under similar conditions a galvanom with a thick wire coil would be unaffected. It was observed considering the Wheatstone bridge method of measuring resista (Chapter V.), that one great advantage pertaining to it is, that making the final adjustment only a very weak current or current at all passes through the galvanometer. It is there practicable in such cases to use a very delicate instrument, and order to prevent damage being done to the needle or its pivot, to prevent the coils being fused by the passage of a heavy curr coil can be shunted until the adjustments are almost com- ted.

It will also be remembered that the instrument need not be any particular design, since the final result is obtained with the edle undeflected; a galvanometer such as this can also be ployed in several methods which have been devised for the mparison of electro-motive forces, in which the instrument is aply used to denote the *absence* of a current, and in which, refore, the consequent advantages are the same as in the case the Wheatstone bridge. Fig. 94 shows the connections for one ch method.

FIG. 94.



E is the standard cell and x the battery whose E M.F. is to be asured. R_1 R_2 are two sets of resistance coils, and G is a icate galvanometer. A certain resistance is introduced into the uit by unplugging the necessary coils in R_1, and the resistance R_2 is adjusted until the current ceases to pass through the vanometer, thus showing that the two points, S and T, have n brought to the same potential. This being the case, then

$$x : E :: R_2 : R_1,$$

refore
$$x = E\frac{R_2}{R_1}.$$

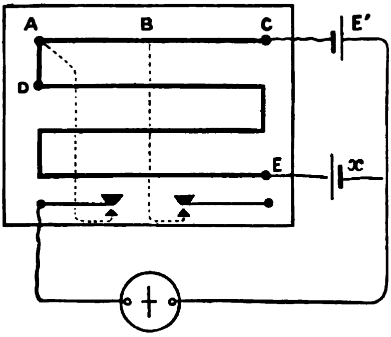
As an example, suppose the Latimer Clark cell to be used as tandard, and R_1 fixed at 1,000 ohms, while the potentials at S d T are equalised by making R_2 5,650 ohms, then

$$x = 1{\cdot}435 \times \frac{5650}{1000} = 1{\cdot}435 \times 5{\cdot}65 = 8{\cdot}108 \text{ volts.}$$

It will be observed that the working out of this example is simplified on account of R_1 being made 1,000 ohms. For th reason it is preferable to always make the resistance in the sa arm as the standard cell some multiple of 10, and obtain a balan by adjusting the other set of coils.

The horizontal galvanometer designed for use with the Wheat stone bridge answers very well for this test, and, as will be see from fig. 95, the bridge itself may be used for th two sets of coils and th the usual key can be em ployed in the galvanomet circuit, while the 'infini plug between A and D c be used to break the batt circuit and so minimise error due to polarisation.

FIG. 95.



When a delicate galva meter is not available, and R_2 must be lower, then the battery resistances become important and cannot ignored. They may, however, be eliminated by increasing of the resistances, say R_1, by a certain amount, say P ohms, obtaining a balance again by increasing R_2 by Q ohms. Then

$$x : E :: Q : P,$$

therefore $$x = E \frac{Q}{P}.$$

The electro-motive forces are, in fact, simply proportional to increase of the original resistances R_1 and R_2.

For example, if after one balance had been obtained, we we to increase the resistance R_1 by 500 ohms, and again obtain balance by adding 2,852 ohms to R_2; then $P = 500$ and Q 2852, therefore

$$x = 1{\cdot}435 \times \frac{2852}{500} = 8{\cdot}185 \text{ volts.}$$

The proof of the method depends upon two laws demonstrat by Kirchhoff, which we will endeavour to explain.

Let the resistance R_1 be slightly reduced, so that the balan upset, then the currents in the three arms will flow in the irection indicated by the arrows in fig. 94.

The first of Kirchhoff's laws (which is almost self-evident in the resent simple case), states that the current flowing to the point S s equal to the sum of the currents flowing from it, that is,

$$C_1 = C_2 + C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

The second law declares that in any complete circuit, even when it forms part of a network, as R_1 E S T, the sum of the products of the current strength in each arm into the resistance of that arm is equal to the sum of all the electro-motive forces in the circuit. That is to say, if in each arm or portion of the circuit the individual resistance of that arm is multiplied by the strength of the current flowing through that resistance, and if all the products so obtained are added together, then the sum so produced will be exactly equal to the sum obtained by adding together all the electro-motive forces in the various arms of the circuit.

The *algebraical* sum must, of course, be taken; for instance, if two currents, or two E.M.F.'s, are opposite in direction, one must be reckoned as *plus* and the other as *minus*.

In the circuit R_1 E S T the only E.M.F. is that of the standard cell, which we denote by E, and, neglecting the internal resistance of this cell, we form the second equation thus:

$$E = C_1 R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

G being the resistance of the galvanometer.

Similarly, in the circuit R_2 x S T, the only E.M.F. is x, but the currents in the two arms are in opposite directions. Therefore

$$x = C_2 R_2 - C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

By inserting in (2) the value of C_1, given in (1), we get

$$E = (C_2 + C) R_1 + C G,$$

that is,

$$E = C_2 R_1 + C R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

From (3),

$$C_2 = \frac{C G + x}{R_2};$$

and, inserting this value for C_2 in (4), we get

$$E = \frac{R_1 (C G + x)}{R_2} + C R_1 + C G;$$

$$R_2 E = C R_1 G + R_1 x + C R_1 R_2 + C G R_2;$$

therefore $$C = \frac{R_2 E - R_1 x}{R_1 G + R_1 R_2 + R_2 G} \quad \ldots\ldots \quad ($$

This equation gives us the value of the current flowing in th galvanometer circuit when the balance is upset, in terms of t various electro-motive forces and resistances. But in making t test we adjust so that no current flows through the galvanomete therefore, when a balance has been obtained, C = 0, and, conse quently, the fraction which forms the right-hand side of equatio (5) is equal to 0.

Therefore, the numerator of the fraction

$$R_2 E - R_1 x = 0,$$

that is, $$R_2 E = R_1 x, \quad \ldots\ldots\ldots \quad ($$

and $$x = E\frac{R_2}{R_1},$$

which proves the case when the battery resistances are so sm as to be negligible.

Equation (6) holds good, in fact, so long as R_1 and R_2 represe the total resistance in their respective arms of the system.

When the resistances of the batteries cannot be ignored, th must be added to R_1 and R_2 respectively to make up the to resistance in the arm, and then equation (6) becomes

$$E\,(R_2 + r_2) = x\,(R_1 + r_1), \quad \ldots\ldots \quad ($$

where r_1 is the resistance of the standard cell, and r_2 that of battery under test. Also, when R_1 is increased by P ohms, and by Q ohms,

$$E\,(R_2 + r_2 + Q) = x\,(R_1 + r_1 + P),$$

that is, $$E\,(R_2 + r_2) + E\,Q = x\,(R_1 + r_1) + x\,P \quad \ldots \quad ($$

Subtracting (7) from (8), we obtain

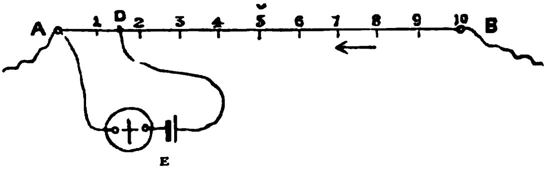
$$E\,Q = x\,P;$$

therefore $$x = E\frac{Q}{P}.$$

There are a number of very beautiful methods for the compa son of electro-motive forces, somewhat similar in principle to th just described. We have selected a few and worked them out length, not only because they are in themselves interesting, b because they involve, in a rather simple form, some very imtant principles and laws which the student will do well to master. We will now direct our attention to a method based upon a ewhat different principle. In this case, again, no current es through the galvanometer when the final adjustment has n made, thus permitting the use of a delicate instrument. But ther very great point in its favour is the fact that the batteries not send any current while their E.M.F.'s are being actually pared. Consequently, the Latimer Clark cell may be used as andard to the best advantage, and the true E.M.F. of a battery ject to polarisation, like the Leclanché, can easily be measured; further, since no current flows through the batteries or the anometer in the battery circuit, their resistances have no effect tever, and therefore need not be known.

If between the ends A and B (fig. 96) of a uniform Germanr wire one metre (39·37 inches or 1,000 millimetres) in length

FIG. 96.



ential difference of 10 volts is maintained, the fall of potential e uniform, say, from B to A. Now it must be possible, under conditions, to find a point in the wire such that the potential ence between that point and the end A shall be any desired on of 10 volts. For instance, between A and the middle of ire, C, the difference is 5 volts. Furthermore, if the negative of the Clark standard cell E is joined to the point A, it will e the same potential as that point, while the end of the wire ected to the positive pole will be 1·435 volts above that tial. A galvanometer may be joined up on either side of E ut affecting the final result, and if the free end of the wire is d to any point near B a current will flow through the galvanor G in opposition to the standard cell, because the potential e point near B is more than 1·435 volts above that at A; while then a point, F, at which the E.M.F. of the battery x is balan is found in a similar manner. Now, the potential differe between A and D is equal to the E.M.F. of the standard cell—t is, 1·435 volts—and the potential difference between A and F equal to the E.M.F. of the battery x. Therefore

$$\text{AD} : \text{AF} :: \text{E} : x.$$

Suppose A D to be 120, and A F 685, divisions; then

$$120 : 685 :: 1{\cdot}435 : x;$$

therefore $$x = \frac{685 \times 1{\cdot}435}{120} = 8{\cdot}19 \text{ volts.}$$

It will thus be seen that it is unnecessary to maintain particular potential difference per unit of length of the wire, this can be immediately found by means of the standard But it is advisable, after the adjustments have been made as ab to verify the result by making contact with both sliders at a the same moment, in order to ascertain whether or not the f potential has varied during the test.

In fact, one great feature in favour of this arrangement is the test may so be made that a slight variation of the pot difference at the ends of the stretched wire need not cause any the source of inaccuracy which has most to be guarded again want of uniformity in the wire itself. By using a *low* resi battery a greater proportion of the fall of potential takes pla the external circuit—that is, along the stretched wire—than a high resistance battery is employed; hence the suitabili secondary cells for this purpose. A greater length of wire ma conveniently obtained by stretching it backwards and for several times upon a board. An instrument based upon foregoing principles for measuring potential differences is c monly called a potentiometer. The wire is sometimes woun a spiral groove round an ebonite cylinder, and, when mad this form, it can easily be divided into 20,000 parts, but this is rarely used for practical work.

In all the preceding methods potential difference is meas indirectly or by comparison. Instruments have, however, b devised which indicate directly, in volts, the difference of pote between any two points; such instruments are called voltme

That invented by Major Cardew is very reliable, and it is at the same time simple in principle. If a wire is heated it increases in length. This linear expansion or extension is proportional to the product of the rise in temperature and the coefficient of expansion for the particular wire. The coefficient of linear expansion is defined as the elongation of a body of unit length when its temperature rises from zero to one degree (Centigrade), and this coefficient or proportional extension for platinum is 0·0000088, so that, for an increase in temperature of 10° C., a yard of platinum wire would be extended to 1·000088 yards. By measuring the amount of extension produced by heating a wire, the increased temperature can therefore be inferred. Now, when a current of electricity passes through a wire it performs a certain amount of work in overcoming its resistance, and the generation of heat is the result.

The rise in temperature resulting from the generation of a certain amount of heat does not, however, bear a simple ratio to that amount of heat. It depends, in fact, upon the time or duration of the current and the specific heat or calorific capacity of the particular substance. The former of these factors is so exceedingly apparent that we need not further enlarge upon it. The specific heat of a body is defined as that quantity of heat which it absorbs when its temperature rises through a given range—say from zero to 1° C.—as compared with the quantity of heat which would be absorbed by an equal mass of water when its temperature is exalted through the same range. If, for example, a pound of mercury at 100° C. is mixed with, or placed in, a pound of water at zero, the temperature of the mixture will only be 3° C., so that, while the mercury has lost 97°, the equal mass of water has only increased 3°, or, in simple language, a quantity of water absorbs about thirty-two times as much heat as an equal weight of mercury, in undergoing the same exaltation of temperature. The specific heat of water being taken as unity, that of mercury is therefore 0·03332. Similarly, the specific heat of platinum is 0·03244.

The variation in the temperature of a wire due to an increment or decrement of heat, depends also upon its weight or its sectional area, for it will be evident that if two wires of similar material and of equal resistance, but of different gauge or different weight—

such, for example, as a given length of platinum wire weigh one gramme, and another platinum wire, twice as long, but weig ing four grammes (offering, therefore, equal resistances)—have th same current passed through them, they will not be raised to t same temperature, although the amount of heat actually develope will be the same in each case. This follows from the fact that i the one case there is more material to heat than in the other.

When a current of electricity passes through a wire, and per forms a certain amount of work in overcoming its resistance, the equivalent of the quantity of energy absorbed in the performanc of this work is seen in the development of a definite amount o heat which is imparted to the wire. The heat (H) developed in unit of time is, in fact, directly proportional to the amount of pow expended in overcoming the resistance of the conductor—that is say, it is proportional to the product of the difference of potenti between its extremities, into the strength of the current C, wh is maintained through it, or $H : E\,C$. If the resistance of the remains constant, the value of C varies directly as E; by doubl E, C is also doubled, and the heat developed then varies as square of E.

Again, the heat unit is defined as that amount of heat wh required to raise 1 gramme of water through 1° C. in tempe and a potential difference of 1 volt maintained through a re ance of 1 ohm develops 0·24 such heat units per second— is to say, the number of heat units, H, developed in *t* seconds,

$$H = 0{\cdot}24 \times E\,C\,t.$$

As $E = C\,R$, it follows that $E\,C = C^2\,R$, so that the form may also be expressed by saying that

$$H = 0{\cdot}24 \times C^2\,R\,t.$$

Collecting all these facts into one simple formula, where represents the rise in temperature in Centigrade degrees, E potential difference in volts, C the current strength in ampe *t* the time in seconds, *h* the specific heat, *g* the weight of the in grammes, and 0·24 the constant which, as pointed out above necessary to obtain a result on the Centigrade scale, we may that

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{C^2 R\,t}{g\,h};$$

o that a current of one ampere, flowing for one second through 1 gramme of water (whose specific heat is 1·0), and offering 1 ohm resistance, involving, therefore, a potential difference of 1 volt, would, if all the energy expended were devoted to the generation of heat, be raised 0·24° C. in temperature.

Similarly, if the same current were maintained through a platinum wire of the same weight and resistance, the increase of temperature would be

$$T^{\circ} = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{1 \times 1 \times 1}{1 \times 0{\cdot}03244} = 0{\cdot}24 \times \frac{1}{0{\cdot}03244}$$

$$= 7{\cdot}4^{\circ}\ \text{C., nearly.}$$

In the Cardew voltmeter a length of very fine platinum-silver wire is employed, and is heated by the passage of the currents whose E.M.F. it is desired to test. In each test, therefore, g and h retain the same values, and by limiting the increase of temperature to a few degrees, the very slight variation of R becomes a negligible quantity. Similarly, by employing a fine wire, it speedily rises to such a temperature that, with any given current, the loss of heat due to radiation equals in amount that which is developed by the current. The only really variable quantities, therefore, are E and C. But, as already pointed out, C varies uniformly with E, and if the facilities for radiation remain the same, the increase of temperature, and with it the elongation, will always be the same for any given value of E. Hence, the amount of elongation can be made to indicate the potential difference maintained between the extremities of the wire.

Simple as the principle is, the construction of a reliable practical instrument is a matter of some difficulty, and an enormous amount of experimental work has been performed in determining the exact sources of error to which a Cardew voltmeter is liable. Fig. 98 illustrates the form of this instrument adopted by Messrs. Goolden after an exhaustive series of experiments extending over a number of years, and in it the inherent sources of variation and error are practically eliminated. The outer casing is removed to show the essential parts as viewed from the back.

The platinum-silver wire is 0·0025 inch ($2\frac{1}{2}$ mils) in diameter, and is fixed at one end to the small brass block *m*. Thence it

FIG. 98.

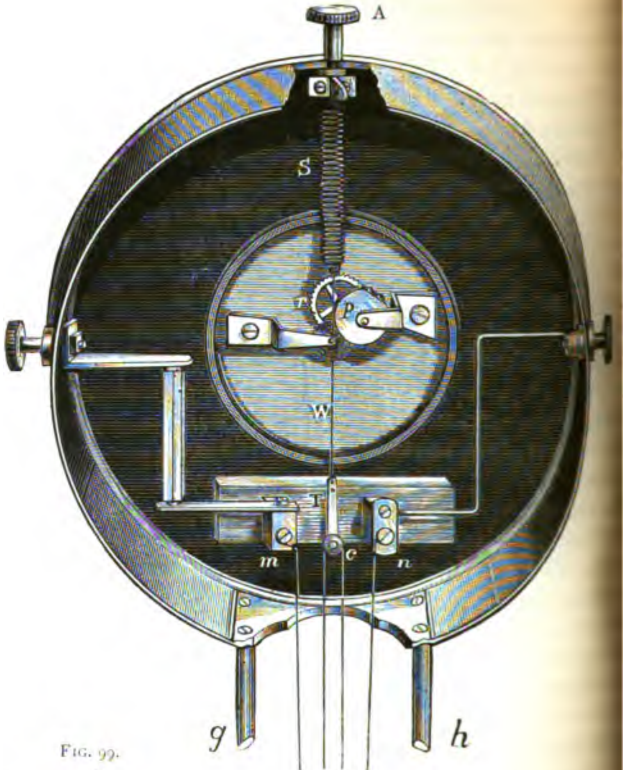
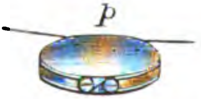
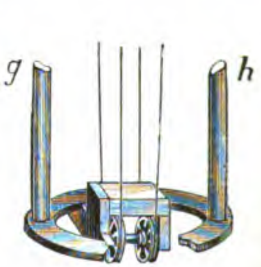


FIG. 99.





led round one of two grooved pulleys supported by a ring at the nds of two metal rods, *g h*, which are about 36 inches long, and re fixed to the brass base-plate. From this pulley the wire returns, nd is passed round a small pulley, *c*; thence it is led to the econd pulley at the top of the rods, and is finally terminated at he small brass block *n*. The brass pieces *m* and *n* are supported y the insulating block of varnished vulcanised fibre, which is ecurely fastened to the brass base-plate, and *m* and *n* are connected each to one of the main terminals of the instrument, which are insulated by ebonite or fibre collars from the brass casing. The wire should pass round the pulleys at the top of the rods in such a manner that a pull at *c* on the two centre wires would cause both pulleys to rotate in the same direction, and, the spindle being pivoted in jewelled holes, the friction is reduced to a minimum.

The small part, *c*, referred to as a pulley, only acts as such during the wiring of the instrument, as the extension of the wire when the apparatus is subsequently used does not cause it to rotate. It is made of vulcanised fibre, with a small groove round its circumference in which the wire lies, and is fixed by a small screw passing loosely through its centre to one end of the thin brass strip T, the other end of which has attached to it a fine platinum-silver wire, W, connected to the spiral spring S. The tension of this spring, which can be varied by means of the adjusting screw A, keeps the wires taut, and when the main terminals are connected to points in a circuit at different potentials, a current passes—say to the block *m*—up the wire, and round the first pulley back to the insulating reel, *c*; thence, again, to the top of the instrument, round the second pulley, and back by way of *n* to the other terminal. This current heats the wire, which expands, and the slack is immediately taken up by the spiral spring S, so that the small brass strip T and the wire W are moved through a distance equal to the expansion of *two* lengths of the heated wire. The amount of expansion (and therefore of the potential difference applied) is measured by observing the distance through which the length of wire W is moved; but as this distance is, at the most, extremely small, some mechanical multiplying arrangement is necessary, and, since the force producing the movement is also very feeble, great care must be exercised in avoiding the introduction of any appreciable friction. This result is attained by th use of a jewelled watch movement. The wire w is led round small pulley, *p*, fixed upon the same spindle as a toothed wheel, which gears into a small pinion, the spindle of which carries a lon needle or pointer, passing over a scale plate at the back of, an not visible in, the figure. When the wire is extended by th current, the spring S causes the pulley *p* to turn through a sma angle, and with it also the wheel *r*, the pinion, and the pointer and, as the diameter of the wheel is much greater than that of th pinion, the pointer is turned through a large angle by a compara tively small extension of the wire

The passing of the wire w round the pulley so as to get a rel able grip, and at the same time avoid friction or risk of damage the fine wire, is a more difficult matter than might at first s appear, and, like every other detail, has received much st before the method now employed was finally adopted.

The pulley is shown separately in fig. 99. It has two nar parallel grooves round its circumference, at one part of w (where it is filed away flat) two set-screws are fixed, both scre up home. The wire is led from T round the first groove to screw-heads, between which it passes over to the second gro in which it completes its journey round the pulley, and is then to the spiral spring.

The wire is so fine that it would not bear being pinched un the screw-heads, but the arrangement described effectually ov comes any tendency to slip; and as the pulley only moves throu a small angle, never making a complete revolution, no sens friction is introduced. Insignificant as this detail may appear is, as already indicated, very important, and the same rem applies to the shape of the spiral spring S and to the material which it is composed. The gradual alteration of this spring found to be the main cause of the slight variation from zero wh was frequently observed in the earlier instruments. It is neces that the tension of this spring should remain constant; and difficulty has been surmounted by (*a*) choosing a spring least li to vary, spiral in form and of German silver, and (*b*) providing thumbscrew A on the outside of the case, by turning which pointer can be readily restored to zero should it become necessar

Although there are four straight lengths of wire equally heated, it will be remembered that the expansion measured is only equal to that of two lengths, for, since *c* does not rotate, its movement would be the same if one of the wires were rigidly fixed to it and the other removed. But it will be noticed that the tension due to the spiral spring is equally distributed between the two wires leading from *c*, and this affords the great advantage that double the tension can be given to the spring, which means that the force with which the pulley *p* is turned can be doubled, and any slight error due to friction correspondingly reduced, without, at the same time, necessitating the adoption of a comparatively thick wire. The wheel work is well made, but it is of course impossible to altogether avoid 'back-lash'—that is to say, as the teeth of the driving-wheel do not fit tight between the teeth of the pinion, the latter does not begin to move absolutely at the same moment that the driving-wheel does when its motion is reversed. To avoid the slight error which this might cause, a hair-spring is fixed to the pinion spindle. This spring is visible in fig. 98, the pinion being immediately behind and therefore hidden by it. It is adjusted so as to maintain sufficient pressure between the teeth of the wheel and pinion to keep them always in contact, so that in either direction the two move simultaneously.

The whole of the casing is of brass, wood, from its liability to warp, being wholly unsuitable ; but it is clear that the rods (*g h*, fig. 98) cannot be made of that metal, as, its coefficient of expansion being higher than that of platinum silver, it would expand more than the wire with any rise of temperature, atmospheric or otherwise, and cause a deflection of the pointer. On account of the expense, platinum-silver cannot be employed for this purpose. Iron has, however, a lower coefficient of expansion than the wire, and the rods are therefore made partly of iron and partly of brass, the length of these parts being so proportioned that the greater expansion or contraction of the brass shall be neutralised by the lesser expansion or contraction of the iron, and the whole rod vary in length in exactly the same proportion as the wire itself. The wires are encased throughout their length by a brass tube which can easily be removed, and the arrangement of the pulleys, together with an opening in the supporting ring to which they

are attached, facilitates the re-wiring of the instrument.
order to prevent damage to the working wire by the accide
passage of a too powerful current, a safety fuse is inserted in se
with it, consisting of a short length of platinum-silver w
0·0014 inch (1⅜ mils) in diameter, which fuses and breaks the
cuit before the current attains sufficient strength to fuse the thi
working wire. This fuse-wire is placed in a slit along the
of a rectangular strip of vulcanised fibre, each end being
minated at a round-headed brass screw in the end of the bl
which is firmly held between two flat springs making contact
the screw-heads, one spring being connected to *m* and the o
to the left-hand terminal. Several such fuse-wire blocks ca
kept at hand, and the replacing of a fuse is then but the wo
a moment. Connection between *n* and the other terminal is
by a stout, stiff wire.

This type of instrument, in which the wires are supporte
the two compound rods, and in which the tube slipped over
simply acts as a casing to protect the wires from air currents
damage, is designed for use with the tube in a vertical posi
the end at which the pulleys are fixed being placed upper
Now, as soon as the wire gets hot, it heats the adjacent air,
being displaced by colder air, rises, and consequently curre
set circulating in the tube. The result is that when the poi
deflected a slight oscillation may be observed, sufficient to pr
the value of the potential difference being read with certai
within half a volt. This oscillation can be entirely eliminate
simply placing the tube in a horizontal position, for the
length of the wire then lies in a more evenly heated atmosp
in which such air currents as rise from it are feebler and
uniform in their distribution in relation to the wire.

A more accurate, though more expensive, instrument is
by dispensing with the rods and fixing the jewelled pulley be
in the end of the tube itself, which, of course, is then compou
being made of brass and iron in the necessary proportions.
instruments are pre-eminently adapted for experimental wor
account of their extreme accuracy, and are, of course, a
employed in the horizontal position. The rod pattern (whic
also be used horizontally) is, however, a first-rate piece o

is for the engine-room or workshop, where a possible error
f a volt in the reading is a matter of little moment, and it
he advantage that the working wire can be more easily
ced than in the tube form. The voltmeter
rated is capable of measuring from 30 to
volts. The calibration is carefully per-
ed, the wire being continually heated by
passage of a current, and stretched, for some
previously, to bring it to its normal con-
n. As it is the heating of the wire which
s a measure of the electro-motive force,
'heating-error' peculiar to most voltmeters
re entirely absent, and the instrument may
nd in fact is, kept continually connected up
ays and weeks together. For the same
n, the reading is unaffected by the presence
ternal currents or any electro-magnetic
and, as iron is not employed and the wire
t coiled, its self-induction is practically *nil.*
e, alternating potential differences can be
red; but it must be remembered that this
absence of self-induction in the instrument,
owing a current to rise suddenly to its full
, limits the range through which the fuse
rotect the working wire; for, although the
acts with certainty if the current rises at all
ally, a very sudden application of a very
E.M.F. would develop a heavy current in-
aneously, fuse and wire being melted simul-
ously.

FIG. 100.

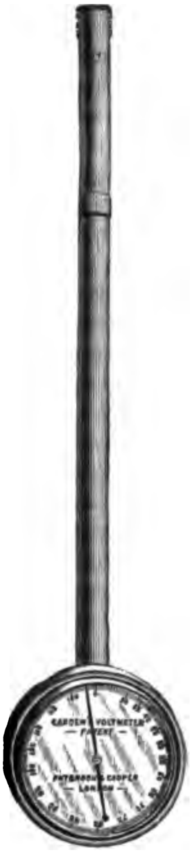
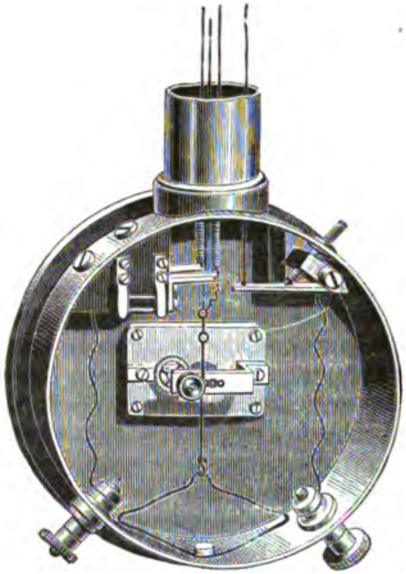


Fig. 100 is a general view of the Cardew
meter as made by Messrs. Paterson &
per, the internal portion of the apparatus,
iewed from the rear, being shown in fig. 101. The instrument
ists of a long piece of platinum-silver wire, 0·0025 inch in dia-
r, and passing up and down the long tube over frictionless
eys supported by the tube. One end of the wire is rigidly
d, the other end being attached to a silk thread which passes

round a small spindle and is kept stretched by means of the
bow-spring shown in the lower portion of the figure. The
therefore, which would otherwise sag or slacken on being hea
is kept taut, acting and reacting with the spring. The spin
round which the thread passes is geared on to the axle carr
the indicating needle wh
travels over the face of
dial ; so that the elonga
due to the varying temp
ture brought about by
different E.M.F.'s can
readily indicated.

FIG. 101.



A fine platinum-si
wire fuse is introduced
tween the brass strips
the left of the figure.
long tube which carries
wire is in two parts, o
brass and the other of
so as to allow it to exp
equally with the wire u
atmospheric changes.

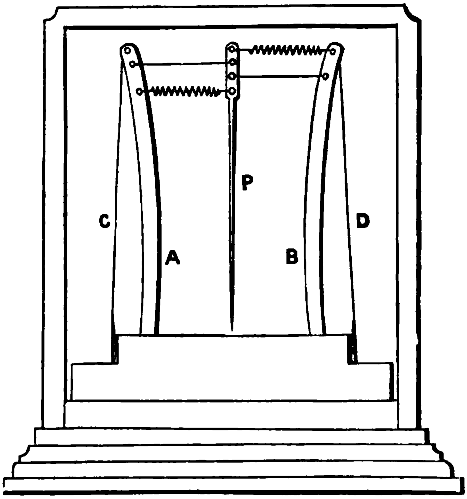
The instruments
usually made to regis
to 120 volts, but the v
of the readings can
easily be increased by inserting in the circuit, in series, resist
coils of various multiplying powers. Thus, if a coil equal i
sistance to the wire in the voltmeter were introduced, it
exactly halve the potential difference of the current at the term
of the voltmeter due to any particular E.M.F. Manifestly, su
coil would have a multiplying power of two, while a coil of
times the resistance would reduce the proportion of pote
difference absorbed by the voltmeter to one-fourth, and then
have a multiplying power of four. These resistance coils,
ever, must not be of the ordinary type. The wire should
platinum-silver, of the same gauge as in the voltmeter, an
order to produce exactly equal facilities for radiation it shoul

are, and, for convenience, it may be stretched over a kind of ectangular framework made by attaching two rods of slate to a ouple of strips of wood, notches being made in the slate to receive he wire and prevent one portion slipping into contact with another. The wire and framework are enclosed by pieces of thin sheet iron.

The ordinary Cardew voltmeter, although the best and most useful instrument for the measurement of high voltages, is not available for the estimation of low potential differences, owing to the exceedingly small elongation due to the slight rise in temperature, and the consequent vagueness of the reading which would result therefrom.

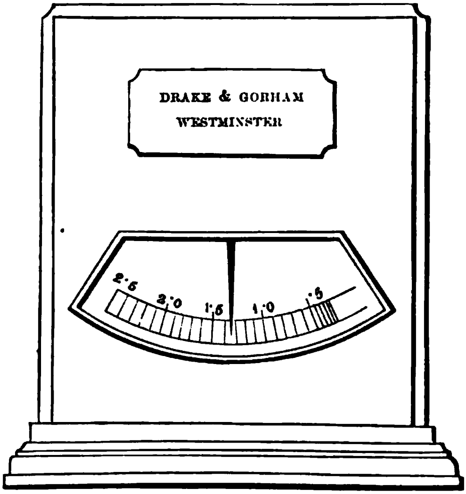
Recognising the necessity for the production of an instrument capable of measuring low E.M.F.'s—more particularly for testing the voltage of secondary cells—Major Cardew has just designed one, the working parts being shown in fig. 102. The range is from 0·5 to 2·5 volts, the scale, as shown in fig. 103, being divided into tenths of a volt.

FIG. 102.



Two pieces of platinum-silver wire, C and D (fig. 102), are kept taut by means of the upright bows, A B. The indicating needle P is supported and held in position by two horizontal pieces of wire and a couple of spiral springs. The lower ends of the wires C D are connected to terminals on the case of the instrument, so that when a current passes through the instrument it travels up one wire and across, by way of the thicker part of the needle, to the other wire. This current raises the temperature of the wires C and D, which, by their consequent ex tension, allow the upper ends of the bows to approach each ot This motion is transmitted by means of the stiff horizontal w to the needle, which therefore travels over the scale from rig left. In the figures the needle is shown over the centre of scale as if deflecte the application of E.M.F. of 1·33 w It will be obser that there is abso no friction—a m important feat which, as a matter fact, renders the strument a possib It is also an inexp sive piece of appar

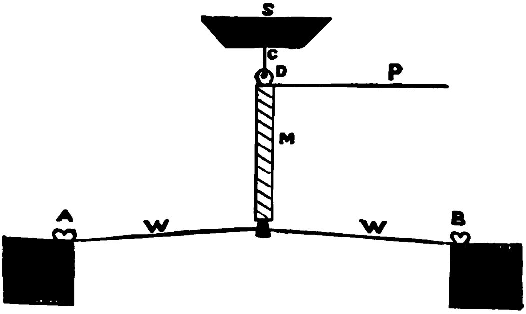
FIG. 103.



Professors Ay and Perry have i duced another, somewhat more c plicated, modific of the Cardew meter, which is c ble of accurately measuring low potential differences, and cating small fractions of a volt. The principle upon which apparatus is constructed will be easily understood by a refe to the diagram, fig. 104. W W is a short piece of plati silver wire, 0·0014 inch in diameter. The ends of this wi held rigidly by the terminal screws A and B. The cent the wire rests in a stirrup supported by the magnifying spri which is similar to that illustrated in fig. 61. The upper of the spring carries a pointer P, and is kept in positio a piece of fine wire, C D, fixed, at its upper extremity, to support S. On a comparatively feeble current—that is to current caused by a small difference of potential—passing th the wire W, it is elongated and the sag is increased. The te on the spring is thereby reduced, and, the lower end being the upper end revolves and carries the pointer with it. The p moves over a dial, and indicates directly the amount of coiling to which the spring is subjected by the sag on the wire. So sensitive is this arrangement that when the initial sag on the wire is comparatively small—that is to say, when the wire is stretched almost in a straight line between the terminals --sufficient change in the sag results from the application of a potential difference of eight or ten volts at the extremities of a wire eight inches long, to produce, when magnified by the spring, a complete rotation of the pointer.

If, in a voltmeter of this kind, the wire is further shortened,

Fig. 104.



the instrument will indicate a still lower potential difference, because the shortening decreases the resistance, and so augments the current resulting from a given potential difference, and also because, the mass of the wire being reduced, its temperature rises higher with a given quantity of heat. But the wire cannot be shortened indefinitely, as it is so fine that the temperature beyond which it is unsafe to work is quickly reached. It is, however, possible to obtain the first-mentioned effect without the second. For instance, in the case of what may be called the bicycle-wheel form of instrument (fig. 105), the whole of the wires can be joined in series, or grouped variously in parallel. In the latter case, the resistance being much decreased, the stronger current develops a greater amount of heat in the spokes, thus affording a means by which an instrument may be used for much lower potential differences than it can be with the spokes in series. The mass

of metal affected by the heat is, however, the same in ei
case.

The design of this form of the instrument is ingenious. Ro
a ring of metal a number of non-conducting studs, A B C, &c.,
fixed. There is also a small non-conducting central piece, P,
which a magnifying spring
attached, at right angles to th
plane of the ring. One e
of the wire is attached to t
stud E, and passes to and f
between the hub or cent
piece P and the various stu
the other end being fixed
the stud F. This device
the advantage that ever
tion of the wire is affec
the current, so that the
need to introduce res
coils into the external
to indicate the higher voltages, all that is necessary bei
already indicated, to join the 'spokes' in series.

FIG. 105.

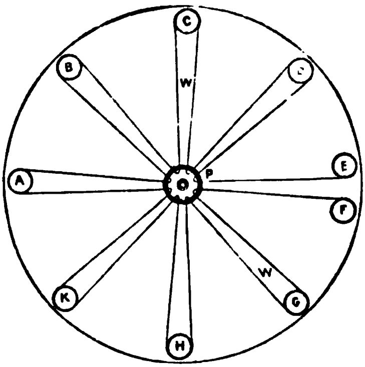
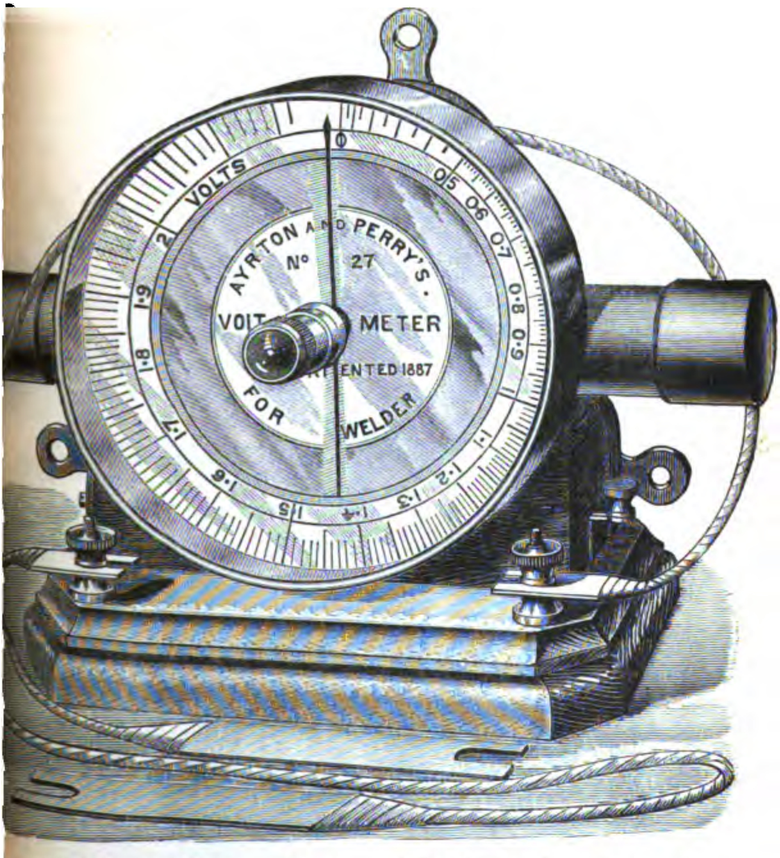


Fig. 106 is a general view of one of these hot-wire volt
constructed to measure the alternating potential difference
terminals of a coil used in electrical welding, which ranges be
1 and 2 volts. The scale is 6 inches in diameter and divid
hundredths of a volt.

In the original instruments, the principle of which is ill
in fig. 104, the pull of the magnifying spring M was counterb
by the pull of the platinum-silver wire W W attached to
minal blocks; but in the recent form, of which fig. 107 is
zontal section, both these pulls act, in order to economise
in the same direction, and are counterbalanced by the flat s
Hence, as the wire stretches, the magnifying spring M is str
and the pointer P (provided with a number of fine hairs for
ing without any great inertia) rotates in front of the dial.
flat spring S has therefore the effect of reducing the dimensio
the instrument, and it also allows of the adoption of a
arrangement for a fuse, to protect the wire from an overs

rrent. In the ordinary Cardew voltmeter, with a wire two yards length, the introduction of a short fuse which will melt with a rrent just too small to damage the instrument does not seriously crease the resistance or diminish the sensibility ; but in this

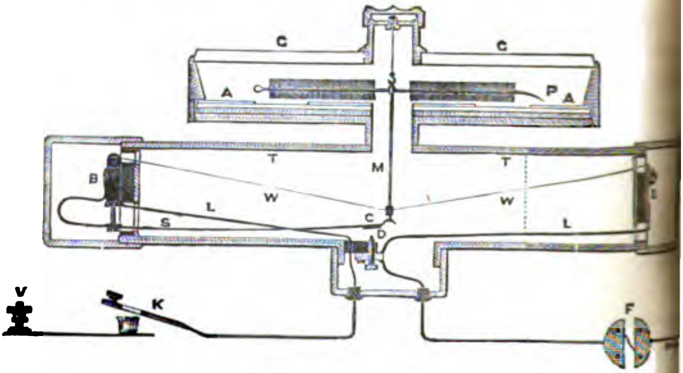
FIG. 106.



modification, which sometimes contains only 8 inches of wire, the introduction of such a fuse would considerably diminish the sensibility, and it is practically impossible to diminish the length of the

fuse in proportion to the length of the working wire, in conseque
of the fact that the metallic blocks to which the fuse-wire
have to be attached would conduct the heat away so rapidly
prevent an extremely short piece of wire from melting. To
come this difficulty a fuse, F, is employed, of such a diamete
it would require a far larger current to melt it than would
to damage the instrument. A small platinum-tipped scre
electrically connected with the wire L, passes through a
insulating block, so that when the wire W W stretches by any
arranged percentage beyond the amount it stretches for the
mum safe potential difference, the platinum contact C on the

FIG. 107.



spring S makes contact with the screw D, and the working
consequently short-circuited. The circuit is then temp
completed through the screw D, a portion of the wire L, an
fuse F, when the current proportionally increases and the
melted without any risk of damage to the instrument. It
that by this arrangement a thick fuse-wire can be employed
ing but a small resistance compared with that of the working
while the sudden application of a potential difference five
times as great as the maximum potential difference the vol
is intended to measure, melts the fuse readily. The fuse F,
and terminals V V are shown, for simplicity sake, detached
the instrument, their actual position being, of course, on the

may be added that the sensitiveness of the instrument
ds in a great measure upon the initial sag given to the wire,
reat care is therefore exercised in this part of the adjust-

e come now to a consideration of the means adopted to
rt the instruments which we described in Chapter IV. as
ble for the measurement of current strength, and which are
ammeters, so that they can be employed as voltmeters.

n ammeter measures directly the strength of the current
g through its coils, and this current is proportional to the
nce of potential at the terminals of the instrument. It
therefore, at first sight appear that any ammeter could be
to measure the potential difference between any two points
ply joining it up to them, observing the strength of the cur-
owing, and from that inferring the difference of potential
maintains it. But the very act of connecting two points in
it by the low resistance ammeter would alter the distribution
potential difference considerably, because an instrument to
re the potential difference absorbed between any two points
portion of a circuit is usually applied as a shunt.

nsequently, although the ammeter so placed would correctly
e the potential difference between the two points *after* they
joined, it would give no information as to their condition

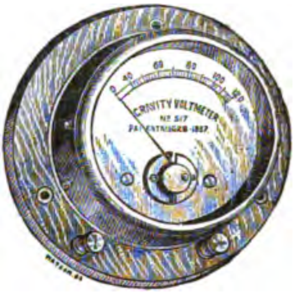
For instance, if a piece of German-silver wire, having
tance of 5 ohms, forms part of a circuit through which a
of 4 amperes is flowing, we know that the difference of
al between its terminals is $4 \times 5 = 20$ volts, since E = C R.
we proceed to measure these volts, by connecting an
er having a fraction of an ohm resistance to the ends of the
e shall get much less than 20 volts, for the resistance, and
re the fall of potential, in that portion of the circuit will
en considerably lowered. Although the total current in the
cuit will be increased by this lowering of the total resist-
ammeter resistance is so low that it shunts the greater
e current from the German-silver wire; and supposing
onsequence, only half an ampere flows through that wire,
tial difference at its ends will be C × R = $\cdot 5 \times 5 = 2\cdot 5$ volts
ead of 20.

In order that the introduction of the instrument should absolutely no alteration, no current at all should flow through and although there are instruments which satisfy this condi the majority are only suitable for use in the laboratory. If, h ever, we take any ordinary ammeter and wind it with a large ber of turns of fine wire, so that it has a very high resistanc can be used as a voltmeter ; for its resistance will be too and the current which passes through it will be too small, to any sensible alteration in the potential difference which measuring ; while, on the other hand, the large number of tu wire will allow the feeble current so flowing to produce a suffici strong magnetic field to actuate the movable part of the appa For instance, one of the ammeters, described in Chapter when wound with fine wire to a resistance of about 2,000 will serve to measure potential differences of from 60 to 120 Of course, it can and must be 'calibrated' for reading in the same way that the ammeter was calibrated for rea amperes.

One important source of error must, however, be g against ; it is due to the fact that a current, in passing thro coils of a voltmeter, heats the wire and increases its resista consequently a given difference of potential will send a current through the coils after they are heated than before. instrument will therefore indicate a lower difference of p than that which actually exists, in consequence of the fac measures the potential difference by the strength of the cur up by that difference. For this reason great care must b cised to prevent the coils of a voltmeter being heated appreciable extent by the current, and in order to secure th dition a key should always be supplied with such an inst The reading can then be taken immediately the circuit th the coils is completed by the depression of the key, and the resistance rises. In the case of an ammeter the resis the coils is so very low that but little heat is generated and, the size of the wire being comparatively great, the te ture, and therefore the resistance, varies but slightly. Fu an ammeter is not used as a shunt, but is placed directly circuit, it is virtually free from this 'heating error,' because ircumstances, the strength of the current flowing through it measured by it is the same as that in the rest of the circuit.

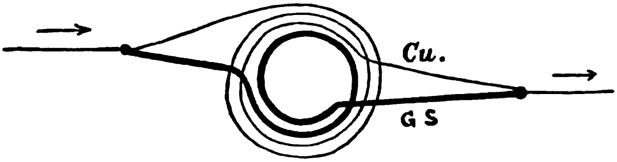
The Shuckert, the Steelyard, and the Eccentric-iron-disc ieters, and many others of a similar character which we have described, can be converted into voltmeters by the simple titution of a long-wire coil of high resistance for the short-wire of low resistance, and this, apart from the calibration, being only essential difference between these types of instruments, e is no need to further enlarge upon them. An exception perhaps be made in the case of Evershed's Gravity voltmeter, eral view of which is given in fig. 108. Its moving parts are ly similar to those of the Gravity eter shown in fig. 67, but, of e, thin wire, offering high resist- is employed. Only a portion s wire forms the actual magnet- coil, this being of copper, while emainder, which is of German is wound round a large metallic ler inside the casing. In an ment indicating up to 110 volts tal resistance would be rather ,000 ohms, that of the actual tising coil being about 200 ohms, so that, with the maximum ial difference, the power absorbed is only 6 watts; and, as emperature coefficient of German silver is low, as also position of the wire gives fairly good facilities for radiation, nperature does not rise appreciably. Consequently, the nent may be left continually on the circuit without causing ror worth noticing under ordinary working conditions.

FIG. 108.



r cases where it is imperative that the indications should be y free from heating error, Mr. Evershed has suggested a very ous method of compensating which may be applied to this similar voltmeter. It is based upon the observed fact that nperature coefficients of metals are different—that is to say, a rise of temperature causes a greater increase per cent. in istance of some metals than of others, the difference in certain such as copper and German silver, being considerable. The magnetising coil proper consists of German-silver wire, a higher resistance coil of copper wire is wound round it in reverse direction, as indicated in fig. 109, the two being conne in parallel, so that the copper coil not only forms a shunt to, opposes the magnetic effect of the other coil, the resultant f acting on the needle being due to the excess of the magnetic e of the German silver over that of the copper coil. The wire of latter is made very thin, to enable the necessary resistance t obtained while keeping the ampere turns sufficiently low, number of ampere-turns in the German-silver coil being se times greater than in the copper. When the current or at

FIG. 109.

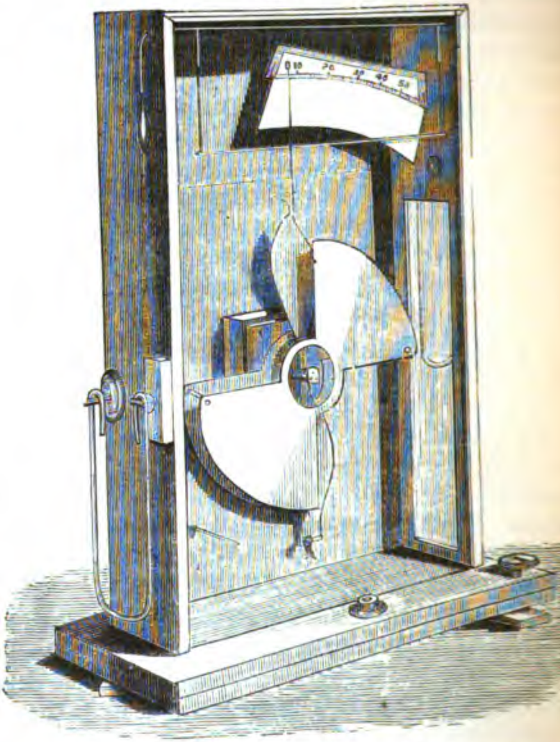


spheric changes cause a rise in temperature, and therefore al resistance, the current in the German-silver coil decreases sl but that in the copper coil decreases in a much faster because the temperature coefficient of copper is so much gr and if the resistances and diameters of the two wires are such that the current in the copper coil decreases just fast e to keep the difference between the magnetic effects of th coils constant, the instrument will compensate itself for any tion in temperature. Unfortunately, the calculations requi somewhat difficult, and the copper wire must be extremely so that this extremely ingenious method has not yet made headway.

In the recent development of electric lighting the tend towards the use of very great differences of potential, much g than any we have hitherto dealt with. In one case, for ins it is proposed to work at a potential difference of 10,000 This potential difference is alternating, thus excluding at o large number of measuring instruments ; and it will read conceived that those which we have described as capa measuring alternating potential differences could not w nodified so as to measure up to 10,000 volts. A voltmeter has een introduced by Sir William Thomson, based upon the well-nown elementary fact that two adjacent bodies at different potentials mutually attract each other. We have seen that a simple way of establishing this difference of potential is to rub two dissimilar substances, such as a piece of flannel and a piece of sealing-wax, together; they will then mutually attract each other, and the force of this attraction might serve to estimate the potential difference between them. But there is a difference of potential between the two poles of a battery; if these two poles are connected one to each of two insulated metal conductors (say brass spheres), the spheres will be at different potentials and will attract each other; the force of attraction is, however, too feeble to cause any perceptible movement, unless very delicate refinements, unsuitable for workshop use, are resorted to. But for this latter fact, such a method of measuring potential difference would be perfect in one respect, for, as the two conductors are insulated, no current whatever would flow from the battery, and we might therefore measure the potential difference without altering it during the act of measurement. The use of this 'electrostatic' method, however, becomes practicable in the case of several hundred volts, and fig. 110 shows Sir William Thomson's voltmeter, which is based upon it.

One conductor is fixed and the other movable; the fixed one consists of two butterfly-shaped sheets of brass, parallel to each other, and metallically connected, but carefully insulated from the rest of the instrument. The movable conductor is a thin aluminium strip, supported at its centre on a knife-edge, and moving freely in a vertical plane exactly midway between the two fixed brass plates. When at rest the movable plate or strip is kept in a vertical position by very small weights placed on a knife-edge at its lower extremity. If a difference of potential is established between the fixed plates and the movable strip, mutual attraction results, and the aluminium tends to set itself in a position, as far as possible, inside the fixed plates, this tendency being counteracted by the weights which it carries. The force of attraction is proportional to the square of the potential difference; the movable conductor, of course, comes to rest when the forces due to the electrostatic attraction and to gravity balance, and this position of rest is indicated by a light pointer moving over a graduated scale. This scale has 60 divisions, which represent equal differences of potential, and a large range is obtained by varying the balancing weights. When a weight of 32·5 milligrammes is used, the pointer

FIG. 110.



moves through one division for a potential difference of 50 v with 130 milligrammes one division corresponds to 100 volts, with 520 milligrammes to 200 volts. But with 10,000 vol upwards there is danger of sparking between the plates in particular instrument ; it is, however, possible to increase the tance between them, and then to measure much higher by ethod. A terminal on the left-hand side of the case is connected the fixed brass plates; while one on the right-hand side is ined to the support of the knife-edge, thus enabling connection be made with the movable aluminium plate. A safety fuse, onsisting of a piece of fine copper wire protected by a glass tube, introduced between the fixed plates and the left-hand terminal, that should a spark dart across between the plates, the fuse, ire will melt and, breaking the circuit, prevent the establishment f an 'arc.'

CHAPTER VII.

ELECTRO-MAGNETS—ELECTRO-MAGNETIC INDUCTION.

IT has been observed that the air space in the neighbourhoo a wire, in which the effect of a current travelling in the wi perceptible, is called an electro-magnetic field, and that the d tion in which the force in this field acts can be made evide means of iron filings, which, if sprinkled upon a sheet of p with the wire passing through it, arrange themselves in conce circles along the lines of force round the wire. And furth will be remembered that some substances offer greater faci than others for the propagation of these lines of force, and th is possible to alter their circular form by bringing near them substance through which they pass with either more or less than through the air. The relative capability possessed by any stance for conducting these lines of force is known as its 'pe ability,' and it is obviously desirable that some method of defi comparing this property in various bodies should be adopted. permeability of air[1] can be taken as the standard, and the meability of all other substances measured by comparison wit

If a piece of hard steel is placed in any magnetic field, of the adjacent lines of force are bent out of their previous s and converge into the steel. More lines of force, therefore, through the space occupied by the steel than passed through same space when occupied by air alone. Hence we conc that the lines of force pass through steel more readily than thr air, or the permeability of steel is greater than that of air. again, the steel is replaced by a piece of soft iron of similar s and size, even more lines of force will now pass through the space, showing that the permeability of soft iron is still greater than that of steel. In fact, the permeability of any substance might be measured by dividing the number of lines of force which pass through it, by the number which pass through the same space when the substance is removed, the strength of the magnetising field being the same in both cases. There is, however, no method available for determining the actual number of lines of force pervading any particular space or substance. The nearest approach to such a desideratum would be to measure the relative strength of any electro-magnetic field, or of any given portion of it, because, as might be supposed, the strength of the field varies directly as the number of lines of force pervading it. But here again we are beset with practical difficulties, for, except in comparatively simple cases, even this is not ascertainable directly, and can only be deduced from other effects.

---

[1] The permeability of a vacuum is taken as unity; that of air is almost c the same, and is a more convenient standard.

It is, however, possible to compare the strength of fields by measuring the magnitude of various phenomena which can be made to take place in them ; one such method is briefly described at the end of this chapter.

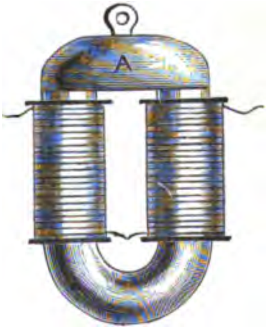
We can thus measure the strength of a field due to any magnetising force—that is, the number of lines of force passing through any given air space—and then, filling that same space with a piece of iron, measure the relative number then passing through the iron. The number of lines of force passing through an area of one square centimetre taken at right angles to them is called the amount of magnetic induction ; the magnetic induction through the air space is equal to the strength of the field (since the permeability of air is 1), and the magnetic induction through the iron, divided by the strength of the magnetising field, gives the permeability of the iron.

By experimenting in this way it has been proved beyond doubt that not only do different substances possess various degrees of permeability, but also that this property may vary considerably in the same substance under certain conditions ; and it is also possible to arrange the various substances in the order of their relative degrees of permeability. The most permeable material known is pure soft iron, and it is found that, generally speaking, as the hardness and impurity of the iron increase, so its permeability decreases; that of hard steel, nickel, and manganese being comparatively low. The vast majority of substances, including most of the other metals, are very nearly equal to air in this respect, while the permeability of a few metals, including bismuth and copper, is less than that of air. To take the two extreme cases, the permeability of iron has been known to reach as high as 19,000—that is to say, 19,000 times as many lines of force have been known to pass through a certain piece of iron than passed through the equivalent air space when the iron was absent, while that of bismuth has not been found to be much below 0·999968.

This property is very important in some practical operations, and (especially in the case of iron) it is useful to know the condi tions under which it varies in the same material. We have alre touched upon a practical application in the case of a helix solenoid, and are now in a position to further consider the ma We observed that the electro-magnetic effect of a helix carryi current can be increased in two ways—either by increasing strength of the current and so increasing the actual number of of force produced, whatever that number may be, or by increa the effect of the available lines of force by making as many them as possible pass through that space near the ends, where will be able to act to the greatest advantage. The permeabili bismuth and copper being less than that of air, either of substances, when placed in an electro-magnetic field, will *decr* the number of lines of force passing through the space which occupies; but even in the case of the most effective subs known, viz. bismuth, the difference is so very slight that it difficult to perceive or measure it. If, however, any subs were to be discovered with a permeability very much less that of air, one way of leading the lines of force through desired space would be to place this substance in that part the field from which it is wished to exclude those lines—that to say, to make all paths but the right one, or the one desired, difficult as possible. But the permeability even of bismuth be so little inferior to that of air, the only available method of at ing the desired end is to make the path which it is desired lines of force should take as easy as possible. In the case of solenoid described in Chapter IV. we wished to increase its eff by leading as many as possible of the lines of force through the ends of the coil, instead of allowing them to leak out at the sides, and for this purpose fitted it with a soft iron core, which had the desired effect. Since the permeability of different qualities of iron varies so much, too great care cannot be exercised in its selection; and, experiment having shown that soft annealed Swedish iron is superior to all other kinds, this should, when the question of expense does not forbid, be used in all cases where it is desired to concentrate the lines of force at any particular point.

It will be remembered that a helix of wire fitted with an iron core is called an electro-magnet, and electro-magnets differ in shape and arrangement according to the work they are intended to perform. Thus, if it were wished with one pole of an electro-magnet to repel a similar pole of another electro-magnet, or of a permanent steel magnet, with as much force as possible, it should be made long and straight, so that its opposite pole might be as far away as possible. It frequently happens, however, that an electro-magnet is required either to support a heavy weight or to attract another magnet or a piece of iron as powerfully as possible. It is then more advantageous to allow both poles of the electro-magnet to act together, and this can be accomplished by making it somewhat similar in shape to a horseshoe, and so bringing the poles close together, as is the case in fig. 111, winding the wire only over the 'legs' of the iron core.

FIG. 111.



In designing an electro-magnet, therefore, the object to which it is intended to apply the apparatus must be kept clearly in view, and it is necessary that the general principles underlying the science of electro-magnetic construction should be now considered, although, under the most favourable circumstances, these laws and principles are somewhat complicated and involved, and, to a great extent, indeterminate.

In the generation of an electro-magnetic field by means of a solenoid there are two prime features to be taken into consideration—viz. the strength of the current and the number of convo tions of wire constituting the coil. It can readily be seen that electro-magnetic effect produced by a current varies directly the strength of that current, so that to double the intensity of field developed by any particular coil it will suffice to double current strength. There is, therefore, no need to take into acco the resistance of the wire, except in so far as it may modify current strength, the resistance varying, of course, directly as length, and inversely as the square of the diameter, of the wire.

As the current strength in any circuit is the same in all par or at all points, of that circuit, the electro-magnetic field develop by any unit length—say one inch of the wire—is exactly equal that developed by any other portion of the circuit of equal leng It follows, therefore, that two convolutions or turns of wire together will generate a field twice as strong as that which can developed by either of the turns taken separately ; and, speak generally, it can be said that the field developed by a solen varies in strength, directly as the number of convolutions. this will be true whatever the nature of the material forming conductor, or whatever its resistance. Nor does the diameter the circle described by the wire when coiled into a long materially affect the strength of the field developed at its cen unless the diameter exceeds about one half the length of the The dimensions of the iron forming the core have also to be into account, but that topic will be considered presently.

Placing these two factors together, then, the field develop by an electro-magnet can be said to vary directly as the curre strength, and directly as the number of convolutions of wire, or

$$\mathrm{M} : \mathrm{C}n,$$

where M is the strength of the field, C the strength of the curre and n the number of turns.

Since C is measured in amperes, this simple formula is quently expressed by saying that the field varies as, or is equal the 'ampere-turns.' As the number of lines of force is prop tional to the length of the wire and the current flowing throu it, it would be more correct to speak of the magnetic effect being proportional to the ampere-feet or ampere-yards ; but he term ampere-turns is generally adopted, we also make use f it.

We stated just now that the diameter of the coil was, with a ertain reservation, immaterial; but it must be remembered that, upposing the number of cells in the battery to be a fixed quantity, ny increase or decrease in the diameter of the coil must proportionally increase or decrease the length of the wire and its resistance, nd cause thereby a decrease or increase in the current strength, nless this variation in the length of wire is accompanied by a corresponding variation in its cross-section, so as to keep the resistance constant. The all-important Ohm's law must always be kept well in view in making any changes of this sort, or serious difficulties will arise. Let us suppose that a wire offering 5 ohms resistance is coiled into a solenoid composed of, say, 10 turns, and forming one single layer, and that a current from 5 cells of 2 volts electro-motive force and 1 ohm resistance per cell passes through the coil. The current strength, supposing the connecting wires to be short and thick, and to have therefore no appreciable resistance, will be

$$c = \frac{10}{5+5} = 1 \text{ ampere},$$

and the field will be proportional to

$$c \times n = 1 \times 10 = 10.$$

If, now, to produce an increased field, another similar layer of wire is wound over the first, the number of turns will be doubled, but the resistance of the coil will be more than doubled, for the diameter of the outer layer will be greater than that of the inner. Supposing, however, the difference in diameter to be so small as to make no material difference in the length of the wire, the current strength will be

$$\frac{10}{10+5} = \cdot 6\dot{6},$$

and the electro-magnetic field

$$0{\cdot}6\dot{6} \times 20 = 13{\cdot}2.$$

Similarly, with a third layer, the current becomes

$$\frac{10}{15+5} = \cdot 5,$$

and the field

$$0·5 \times 30 = 15·0.$$

The multiplication of the layers, therefore, does not pro tionally increase the strength of the field. On the other hand, consumption of materials necessary to the generation of the c rent is reduced, and the economy of the system proportion increased. If, therefore, a coil of 99 layers were employed, supposing for the moment all the turns to be of uniform le and resistance, the arrangement would be very economical, for current would be only

$$\frac{10}{495+5} = ·02,$$

while the field would be

$$0·02 \times 990 = 19·8.$$

But, of course, the length of wire composing the ninety layer would be considerably greater than that forming the Now, the circumference of a circle varies directly as its dia and is equal to $2 \pi r$, where π is the ratio between the circu ence of a circle and its diameter, or 3·1416, and r is the radi the circle. If, therefore, the diameter of the outside lay actually twice that of the inside, the length of the wire in ea the larger turns, and consequently in the whole layer, wil exactly doubled, and its resistance doubled also; and the inte diate layers will vary proportionally. But the actual resistanc the whole coil can be easily calculated, for if the radius of the in layer is half an inch and of the outside layer one inch, the m or average radius will be three-quarters of an inch—that is to the length of wire in the fiftieth layer will be half as long agai that in the first. Its resistance will therefore be 7·5 ohms. S larly, the resistance of the first and last layers together wil 15 ohms, or an average of 7·5 ohms per layer, and this will be t of every similarly situated pair of layers, so that the total resist of a number of layers is equal to the resistance of the middle average layer multiplied by the number of layers. In the c under consideration the resistance will be

$$R = 7·5 \times 99 = 742·5,$$

he current strength

$$\frac{10}{742{\cdot}5+5} = {\cdot}0133,$$

he electro-magnetic field

$$0{\cdot}0133 \times 990 = 13{\cdot}167.$$

f, now, we suppose the number of layers to be again doubled, the mean radius increased thereby to 1 inch, the mean or ge resistance will be 10 ohms per layer, and the total resist- of the 198 layers 1,980 ohms. The current then becomes

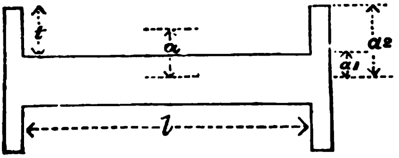
$$\frac{10}{1980+5} = {\cdot}005,$$

the electro-magnetic field becomes

$$0{\cdot}005 \times 1980 = 9{\cdot}9.$$

he addition of layers of wire after a certain point has been ed has the result, therefore, of so increasing the proportional ance as to reduce the effect which can be developed by any battery, and this limit of usefulness or efficiency is reached the maximum radius is twice that of the bottom or first layer. hen the field due to a certain coil, with inside and outside s having resistances of 1 : 2, is insufficient for a given purpose, y become advantageous to re-wind the bobbin with wire of a ler gauge, so as to get ater number of turns the same compass. A nce to the diagram, 12, will simplify the difficulties involved consideration of this r. Let us suppose the figure to represent a wooden or ite bobbin, and that the length, *l*, of the space occupied by oil or the distance between the 'cheeks' of the bobbin, is hes, while the radius, a_1, of the bottom layer to be wound is rter of an inch, and the extreme radius, a_2, of the coil three- ters of an inch. The mean radius a will be half an inch, or

FIG. 112.



$$a = \frac{a_1 + a_2}{2} = {\cdot}5.$$

The total thickness, t, of the coil or of the layers will also half an inch, or

$$t = a_2 - a_1 = \cdot 5.$$

As we have already seen, the length of one turn of wire radius a_1 will be $2\pi a_1$, and, it there are n turns in that layer, length of wire composed in it will be $2\pi a_1 \times n$. Supposing th to be m layers in the coil, having the mean radius a, the length L will be

$$L = 2\pi a \times n \times m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad ($$

Now, as, in winding a number of layers of wire in a coil, each must somewhere or other *cross* the subjacent turn, it follows the turns of any one layer cannot be placed evenly in the gro or recesses between the turns of the layer immediately underne it; or, in other words, if we assume the wire, with its insu covering, to have a diameter, d, the section of the space occ or appropriated by that wire will really be a square whose si equal to d. Consequently, in one layer the number of tu will be

$$n = \frac{l}{d},$$

and the number of layers, m, will be

$$m = \frac{t}{d}.$$

Substituting these values for m and n in (1) we get

$$L = 2\pi a \times \frac{l}{d} \times \frac{t}{d} = \frac{2\pi a \times l \times t}{d^2} \quad . \quad . \quad . \quad .$$

For example, let the diameter of the wire, with its insu coating, be 50 mils (the mil is the thousandth part of an then the length of this wire that would be required to fi bobbin illustrated in fig. 112 would be

$$L = \frac{2(3 \cdot 1416) \times 0 \cdot 5 \times 3 \times 0 \cdot 5}{(0 \cdot 05)^2} = 1885 \text{ inches} = 52\tfrac{1}{3} \text{ yards.}$$

We are thus able to calculate not only the length of required to fill any bobbin, but also its resistance, the resis per unit of length being ascertainable from tables. Moreover, l number of turns of wire can be easily calculated, for, *m* being number of layers, and *n* the number of turns in each layer product *m n* will give the total required, but

$$m = \frac{t}{d}, \text{ and } n = \frac{l}{d};$$

$$\therefore\ m\,n = \frac{t\,l}{d^2},$$

$$\text{or } m\,n = \frac{0{\cdot}5 \times 3}{(0{\cdot}05)^2} = 600 \text{ turns.}$$

If, for the sake of simplicity, we suppose the wire employed to a resistance of 0·1 ohm per yard, the current, with the same ery as that previously used, will be

$$c = \frac{10}{5{\cdot}23 + 5} = 0{\cdot}977,$$

the field developed will be

$$0{\cdot}977 \times 600 = 586{\cdot}2.$$

ls in the previous example, so in this, doubling the number yers reduces the effective power of the coil. In working this it must be observed that t_1 now becomes 1 inch ; therefore, the mean radius (a_4) of a_3 and a_1 becomes

$$\frac{a_3 + a_1}{2} = 0{\cdot}75,$$

$$\text{L} = \frac{2\pi a_4 \times l \times t_1}{d^2} = \frac{2(3{\cdot}1416) \times 0{\cdot}75 \times 3 \times 1}{(0{\cdot}05)^2} = 5654 \text{ inches}$$

$$= 157 \text{ yards};$$

nce

$$c = \frac{10}{15{\cdot}7 + 5} = 0{\cdot}483,$$

, the number of turns, *m n*, being 1,200, the field developed be

$$0{\cdot}483 \times 1200 = 579{\cdot}6,$$

omewhat less than with only 600 turns.

Let it now be supposed that a given bobbin—say of the ensions shown in fig. 112—is to be filled with copper wire ich shall offer a definite resistance, say 5 ohms. There are thus only three quantities known, viz. the dimensions of the bobbin, the resistance which the coil is to offer, and the specific resistance of the copper; while the length of the wire and its diameter are unknown and require to be ascertained. The space in which the wire is to be wound can be calculated from the given dimensions, for, V being this space or volume,

$$V = \pi\, l\,(a_2^2 - a_1^2), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

$$\text{or } V = 3{\cdot}1416 \times 3({\cdot}75^2 - {\cdot}25^2)$$
$$= 4{\cdot}7124 \text{ cubic inches.}$$

But supposing, as will be actually the case, that the wire, whose diameter is *d*, occupies the same space that it would take were it to be square instead of round, then, manifestly,

$$V = L \times d^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

As, also, the total resistance of the wire varies directly as its length, directly as its specific resistance *s* (which, in this case, we take as the resistance per cubic inch), and inversely as the area of cross-section of the wire,

$$R = \frac{L \times s}{area}.$$

But the area of the insulated wire is equal to πr^2, or $\pi\left(\frac{d}{2}\right)^2$, that is, $\pi\frac{d^2}{4}$.

Therefore $$R = \frac{L \times s}{\pi\frac{d^2}{4}},$$

that is, $$R\,\pi\frac{d^2}{4} = L\,s,$$

or $$R\,\pi\,d^2 = 4\,L\,s,$$

and $$d^2 = \frac{4\,L\,s}{R\,\pi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

But from (2) it will also be seen that

$$d^2 = \frac{V}{L}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

Consequently $$\frac{4\,L\,s}{R\,\pi} = \frac{V}{L}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5).$$

and
$$4\,L^2 s = \pi\, R\, V.$$

Therefore
$$L^2 = \frac{\pi\, R\, V}{4\, s},$$

and, finally,
$$L = \sqrt{\frac{\pi\, R\, V}{4\, s}} \quad . \quad . \quad . \quad . \quad . \quad (6).$$

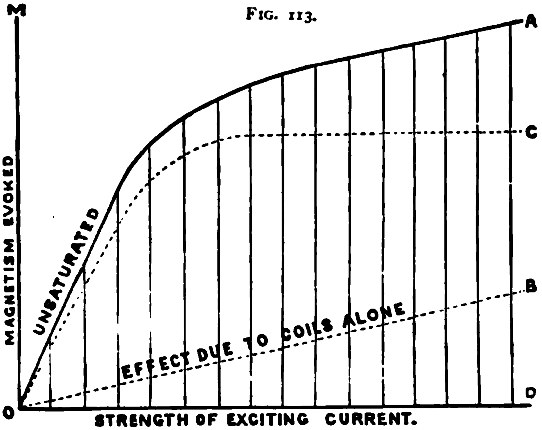
By inserting the numerical values on the right-hand side of this equation, the length L, having the required resistance, can therefore be found, after which we can, by equation (4), determine also the gauge of the wire. It must, however, be noted that, for simplicity, d is taken as the diameter of the bare wire in equation (2), thus rendering the result only approximate; but when the thickness of the wire is great as compared with that of the insulation, the formulæ approach very closely to the truth.

It is frequently useful to know the exact length of any particular wire which can be wound on any particular bobbin, and, knowing V and d, this can be easily ascertained, for, if d_1 represents the outer diameter of the wire and its covering, V the volume of the wire-space, and L the required length, then

$$L = \frac{V}{d_1{}^2}.$$

So far, very little has been said concerning the dimensions and nature of the core, beyond the fact that it should have the highest possible degree of permeability, and be constructed, therefore, of the best annealed iron, and that there is a limit to the number of lines of force which can easily be passed through an iron core. These considerations render necessary the employment of a relatively massive core, having, for the best electro-magnetic effect, a diameter equal, at least, to the thickness of the coil with which it is to be surrounded—that is to say, its diameter should correspond to the thickness t in the ideal coil illustrated in fig. 112. It is here that the question of relative permeability has to be taken into consideration, for it has been experimentally demonstrated that there is a limit to the number of lines of force that can be transmitted by a given mass of iron, and that this limit is soon exceeded when the diameter of the core of an electro-magnet is small as compared with that of the coil which surrounds it. The permeability of a rod of iron decreases as the lines of force passing through it increase, so that, beyond a certain point, a considerable increase in the strength of the current makes but little difference in the electro-magnetic force developed at the poles. When it thus becomes very difficult to urge additional lines of force through a piece of iron, it is said to be magnetically 'saturated,' but no definite point has yet been reached at which it can be said to be absolutely impossible to increase the number. Many definitions of the so-called 'saturation' point have been given, but they are generally based upon a misconception of the question, and some of them are altogether misleading. There is abundant evidence of this, if evidence were wanting, in the fact that no two authorities have yet been able to agree upon the saturation point even of iron, to say nothing of steel, and the majority are satisfied by referring to historic experiments, which, however, were made at a time when iron, such as is now in every-day use, was unobtainable. As a matter of fact, if 100 different samples of iron were taken and experimented upon, it is more than likely that as many different results would be arrived at, for the saturation point depends solely upon the permeability, and the permeability of any particular piece of metal depends greatly upon its molecular structure. Now, the permeability of air is constant, although it is low as compared with a piece of 'unmagnetised' iron. In other words, there is no magnetic saturation point for air, so that, through an air-space which already has a great number of lines of force traversing it, it is as easy to urge more, as it would be if there were none already in existence. It follows, therefore, that at a certain stage of the magnetising force developed in or by a coil of wire, the permeability of air equals, and beyond that stage exceeds, the permeability of iron. A consideration of these points demonstrates that the core of an electro-magnet should be sufficiently massive to prevent the saturation point being reached, or, at any rate, passed, when the maximum current which it is intended that the coil shall carry is passing. This will be evident by a reference to fig. 113, in which the relative strengths of the magnetic field under different conditions are shown by the 'curves' plotted out on a sheet of 'squared' paper. This squared paper is exceedingly useful. It is usually ruled with a number of equidistant horizontal and vertical lines, the former being, however, omitted in the present istance. Let it be supposed that the line O D is divided into a umber of equal parts, corresponding to the various current rengths, so that from O to the tenth division would represent five mes the current strength that would be indicated by two such ivisions. Let us also suppose that O M is divided equally, and at the divisions correspond to the various magnetic effects prouced by an electro-magnet upon a compass needle balanced at me distance from it, and in the same horizontal plane as the axis f the coil. Let us now suppose currents of various strengths, dicated by the distances along O D, to be sent through the coil,

FIG. 113.



he effect which the coil with its core exerts upon the compass eedle can be marked off from the line O M upon the various ordinates projected from O D. The thick upper curve O A drawn hrough the intersecting points shows graphically, by its distance om O D, the deflecting effect produced upon the needle by the arious currents corresponding to the distances along O D. Let it e further supposed that, without in any way altering the position f the needle or of the coil, the core is withdrawn and the various urrents again sent through the coil. Then the various magneti ffects of the coil upon the needle are clearly indicated by th curve' O B, which, in this case, is a straight line, and whi emonstrates, therefore, that the field produced by the coil is pr portional to the current flowing through it. The third curve O C is particularly interesting. Suppose the magnetic effect due to the coil alone, and represented by the distance D B, to be deducted from the joint effect produced with the same current by the core and coil combined, and represented by the distance D A, then the remainder D C will represent the effect produced by the core alone. And if this subtracting process is carried out along each of the ordinates, the curve O C, known as the curve of magnetisation, will be produced. Now, it will be observed that, after a certain point has been reached, this curve becomes a nearly horizontal straight line, indicating that the saturation point of the iron has been reached, and that any further increase in the current strength does not add appreciably to the magnetisation of the core, the increase in the strength of the field developed being that due to the coil itself. The two curves O C, O B, would, if the experiments were carried far enough, intersect, at a point where the permeability of the air equals that of the saturated iron.

Pure soft iron has another property which recommends its adoption for the cores of electro-magnets, and that is its low 'retentivity,' for, as a rule, electro-magnets are required to develop as strong a field as possible at some particular point directly the current commences to flow, and to lose or be deprived of all traces of magnetisation on the cessation of the current. Steel, as we have already seen, always retains a large proportion of the magnetic state impressed upon it by the projection of an electro-magnetic field through it, or, in ordinary language, it retains the magnetism imparted to it. Hard and impure iron have similar properties, inferior only to steel itself. There is no doubt that these properties of permeability and retentivity are very largely governed by the molecular structure of the iron or steel, and by the greater or less rigidity obtaining among the particles of the metal. In fact, the two properties go together; for all qualities of iron or steel through which it is difficult to urge the lines of force, or to magnetise, are found to be correspondingly obdurate when it is sought to demagnetise them, or deprive them of magnetisation. There is, therefore, a double gain in employing pure soft iron, for not only is its permeability greater, but its retentivity is also less than that of impure or hard iron.

On the other hand, in selecting a material for permanent magnets, the principal thing to be considered is the retentivity, which, of course, should be as high as possible. No substance has yet been found which is, in this respect, superior to good hard steel. Some specimens of steel have been made so hard that fforts to magnetise them have proved futile. One of the most emarkable features to be observed in this matter is the extraordinary effect produced by the admixture of a small—one might almost say a minute—proportion of other, or foreign, substances with the iron. Just as a fractional proportion of iron or other metal added to copper causes a large increase in its electrical resistance, so the addition of carbon, tungsten, phosphorus, sulphur, arsenic, &c., to iron, reduces its permeability and also increases its retentivity. This reduced permeability corresponds, in many respects, to increased electrical resistance in a conductor, and is, in fact, sometimes referred to as increased magnetic resistance. In the case of ordinary steel the retentivity is evidently due, in a great measure, to the presence of carbon, and, with a bar of good magnet-steel, the permeability is so feeble, and the retentivity so great, that it is impossible, by electro-magnetic induction, to upset the molecular arrangement in the interior of the bar, so that the magnetisation is in reality only skin-deep. This can be easily proved by magnetising a small piece of very hard steel and then immersing it in dilute sulphuric or hydrochloric acid. In a few moments the surface of the metal will have been dissolved, and on withdrawing it from the liquid all trace of magnetisation will have disappeared. Consequently, it is preferable, in making a large permanent magnet, to build up a number of thin strips of steel cut to size and then magnetised separately. On fastening them together, the built-up, or 'laminated,' magnet will be found capable of producing a far stronger field than can be obtained with any solid magnet of similar dimensions. It should, however, be added that in building up a compound magnet, or 'magnetic battery,' there is no advantage in employing *brass* screws or bolts to fasten the individual magnets together as is usually done. In fact, this plan cannot but disperse the lines of force passing through the magnets, and therefore weaken, more or less, the polar strength. Iron screws or bolts are mechanically and magnetically preferable.

It is interesting to notice that specimens of steel have been made, containing 12 per cent. of manganese, which it has been found practically impossible to magnetise even under the influence of a very powerful field. Probably, the magnetic reluctance, molecular rigidity, magnetic inertia, or whatever else we may choose to call that property of steel which our forefathers knew as coercive force, is so great, that to overcome it is impossible. Similar results follow when the proportion of carbon, phosphorus, sulphur, &c., mixed with the iron exceeds a certain small limit, while the admixture of even the smallest percentage of antimony suffices, it is alleged, to destroy all trace of magnetic properties. There should certainly be a large field of practical utility open to the economical manufacture of unmagnetisable iron. For example, the bed-plates of dynamos are sometimes—and used to be even more extensively than now—separated from the field-magnets by huge slabs of zinc, because, otherwise, they would form what may be called a magnetic short-circuit between the poles of the field-magnets. Zinc is mechanically much weaker than iron, and this, added to its very much higher price, renders its use highly objectionable. To avoid the difficulty, dynamos are rarely designed now with their pole-pieces downwards, but are turned about so that the bed-plate is connected to the yokes or magnetically neutral portions of the field-magnets. Under such circumstances only a very few of the lines are wasted by passing through the bed-plate. Reverting to the question of magnetic inertia, it may be mentioned that any cause which may operate to set up molecular vibrations in a piece of iron or steel facilitates either magnetisation or demagnetisation—that is to say, if the metal is placed in a magnetic field and then vibrations set up in it, it will be more readily and more powerfully magnetised than would be the case were the vibrations not set up; and, conversely, a magnet loses its magnetisation by being set in vibration, due to the fact that facilities are thereby afforded for the individual particles, which are themselves magnets, to partially rotate and form little closed magnetic circuits in the mass of the metal. These vibrations can be caused by heating, hammering, twisting, or any other similar violent treatment. Hence, steel magnets should always be placed down gently, and never dropped or thrown down, otherwise the magnetisation will be more or less destroyed.

A magnet raised to a red-heat loses its magnetisation entirely, and this can easily be demonstrated by heating a magnetised sewing needle in a gas flame.

By adopting the precautions referred to, magnets can be made capable of sustaining considerably more than thirty times their own weight, but a description of the method practically adopted for the manufacture of permanent steel magnets capable for some years of supporting about twenty-five to twenty-eight times their own weight may prove serviceable. In this case, the best tungsten steel is employed. It is heated gently to a dull red heat and hammered into the required shape, care being taken not to raise the temperature too high, or the tungsten will be volatilised. A small magnet may therefore require to be placed in the fire several times before the necessary shape has been obtained. This process being completed, the steel is then hardened by being first placed in a close fire out of contact with air, so as to ensure uniform heating and to prevent the formation of a hard scale of iron oxide. It is then dipped into a water bath. This latter process must be carefully attended to, or the metal will be twisted or otherwise distorted. It should be held vertically, and, if of the horse-shoe pattern, its extremities should be dipped in first, the metal being steadily lowered into the water. The next process is that of polishing, after which it is passed a few times over the poles of a large and powerful permanent magnet, the steel being turned over once or twice so as to magnetise both faces. Of course, a large electro-magnet, with a powerful current circulating through its coils, can be employed, but the other form is quite efficient and certainly much less troublesome.

We have not yet, however, said all that requires to be said upon the subject of electro-magnets. One important detail, so far neglected, is the length of the coil and of the core, as compared with the diameter. It has already been laid down that the maximum, or outside, diameter of the coil should not exceed three times the diameter of the core; but although it is often stated that the best result is obtained when the length of the core is six times its diameter, we have failed to discover any universal reason for such a proportion. As a matter of fact, with a bar-magnet, where we desire to employ only one pole, and wish to mask or get rid of the effect of the other, there is a decided advantage in using a core of much greater proportional length, and if we are restricted as to the quantity of wire to be employed, we can then wind fewer layers over a long piece of iron than would be wound over a shorter piece. By so doing we should reduce the distance between the iron and the wire, and therefore, with the same resistance, the number of lines of force passing through the core would be correspondingly increased. Supposing, however, the same proportion to be maintained between the respective diameters of the lengthened core and its coil, and the gauge of the wire increased so as to maintain a constant resistance and constant number of turns, the polar strength developed close to one end of the core will vary as the square of the length of the core, providing, however, that the core is not so extensively lengthened as to cause many of the lines of force to 'leak out' at the sides of the coil. This limit will, of course, vary with different qualities of iron, as the question is mainly one of relative permeability. Sometimes there is an advantage in using very short electro-magnets, as, for example, when it is desired to obtain one which shall respond promptly to variations or reversals of the magnetising current.

So far, we have only considered electro-magnets in which the wire is wound evenly throughout their length, but, for some purposes, it is preferable to vary the method of winding. If, for example, it is desired to construct a bar-magnet which shall develop a very powerful field close to its extremities, but which is not wanted to exert any force at a comparatively greater distance, then the best form to give to the piece of apparatus is that in which the wire is 'coned up' near the ends—that is to say, where a large number of layers is wound over the ends, the number decreasing towards the middle, few or none being wound over the central portion of the core, although at no point should the wire, as a rule, be wound to more than three times the diameter of the core. The lines of force in such an electro-magnet will be powerfully developed near the ends, and there will be little tendency for them to leak out. On the other hand, they will make much smaller air-curves than would result from an equal length of wire wound evenly along the entire length of the core.

The horse-shoe form is only adopted when it is desired to ert the maximum attraction upon a piece of iron placed near it. it were placed at any considerable distance compared with the tance between the magnet poles, most of the lines of force uld pass across the air space from one pole to the other without tering the iron. But such a magnet obeys the same law that lds good for bar magnets so far as the relative strength of the gnet, when traversed by various currents, is concerned. That to say, if we have an electro-magnet developing a field, at a ren distance the strength of the field will vary directly as the rength of the current producing it. When, however, a piece of ft iron is placed in the field, the lines of force are diverted, and, ssing through it, endow it with magnetic polarity, and the larity developed varies directly as the number of lines passing rough it, or as the strength of the current. Such a piece of iron called an armature, but we may regard it for the time being as other magnet, and when we have two magnets mutually attract- g one another, the force of attraction is proportional to the pro- ct of their magnetic strengths, or the force

$$f : m \times m_1,$$

ere m is the strength of one magnet, and m_1 that of the other of the armature).

If, now, we suppose the strength of the current to be doubled, d consequently the magnetic field developed to be also doubled, m (assuming the iron to be far from saturated) twice the mber of the lines of force will pass through the armature, the gnetisation of which will therefore also be doubled, that is

$$f_1 : 2m \times 2m_1 = 4mm_1,$$

doubling the current strength, quadruples the magnetic attrac- n. Hence this attraction at any given distance varies directly the square of the strength of the current flowing through the il. When, however, the iron approaches saturation, the altera- n in its permeability prevents any definite law being formulated.

This law is sometimes mis-stated by saying that $m = m_1$, ence $m \times m_1 = m^2$. But this is only true when the whole of e lines of force emanating from the poles of the electro-magnet pass through the armature, and this rarely or never happens.

To ensure that the armature shall be capable of transmitting a large percentage of the number of lines of force which pass through the core, it is evident that it must at least be equal in permeability and correspondingly massive. It should certainly be equal in section to the core.

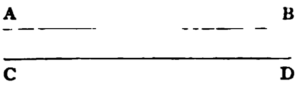
One of the best forms of the horse-shoe magnet is that illustrated in fig. 111. It will be seen that the coil is divided into two sections, placed one on each limb or leg of the core, the winding being such that, were the core straightened out and the coils pushed together so that their ends meet, they would form one continuous coil or helix. Otherwise similar instead of dissimilar poles would be developed at the extremities of the core. The iron should be the best and softest procurable, and should be bent round so that the poles are close together; a comparatively very large number of the lines of force will then pass through the space between the poles when the armature is removed. The surfaces in contact should fit as perfectly true as possible, so that there is the minimum air space between them. Sharp corners or edges should be avoided, and, since the natural shape of the lines of force is circular, the whole should approximate to the circular form, when there will be little tendency for the lines of force to 'leak out' of the iron and complete their circuit through the air space.

Horse-shoe electro-magnets are frequently constructed to sustain a weight. The sustaining power must not, however, be confounded with the strength of the field or the magnetic strength, as this power depends upon a number of secondary considerations, such as the shape and smoothness of the pole pieces or extremities of the core, the dimensions and surface of the armature, the method of applying the weight to be sustained, &c., which do not require to be taken into account when estimating the electro-magnetic field itself. The weight can be suspended from a hook fixed to the middle of the armature, so that the pull upon the two poles is equal, the sustaining power being measured by the weight which can be supported by the armature without causing its separation from the magnet.

It is, however, frequently preferable, for convenience of construction, as in the case of most forms of dynamo-electric achines, as well as in telegraphic and other similar apparatus, to uild up an electro-magnet in which two straight cores are yoked gether by a piece of soft iron which is screwed or bolted to em. The yoke must naturally be massive, and the surfaces fit uly to avoid as far as possible the introduction of a magnetically esisting air space.

We have stated frequently—so frequently, in fact, that we almost feel it necessary to apologise for repeating the statement—that when a current of electricity is set up in a wire, an electro-magnetic field is almost immediately generated in the region surrounding that wire. But the converse of this is also true—viz. that when an electro-magnetic field is suddenly set up around a wire, there is a tendency for a current to be generated in that wire *during the setting up of the field*, and if the wire forms part of a complete circuit a current will flow along it. The source of the field is immaterial: it may be a permanent magnet, a straight wire or a helix carrying a current; all that is essential being that the lines of force should be thrust across the wire, or that the wire should be moved in such a manner as to cut the lines of force *transversely*. As an instance, let A B, C D (fig. 114) be two wires running side by side for a certain distance, each forming part of a complete circuit. If a current is started in A B, lines of force will immediately start from its centre, or axis, in the form of widening circles, and, cutting the second wire, C D, set up an electro-motive force therein and, in consequence, generate an electric current. It is only, however, while the lines of force are actually cutting the second wire that the E.M.F. is developed, and as this cutting ceases immediately the current in A B arrives at its full strength, the induced current lasts but for a moment. In direction it is opposite to the current in the wire A B. While the original current is steady many of the lines of force due to it are embracing the adjacent wire C D, though, being relatively at rest, they have no effect thereon.

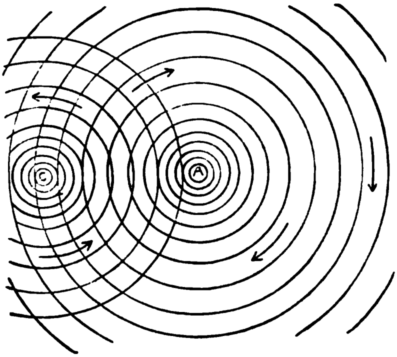
FIG. 114.



But when the current in A B is stopped, all the lines of force collapse upon it, and those which extended beyond the wire C D again cut it, and thereby induce in it another momentary current.

But, since the lines now cut the wire C D in the opposite sense (for they approach it from the opposite side), the resulting current is in the opposite direction to the previous one—that is, it is now in the same direction as the inducing current which was flowing in the wire A B. By noting the direction of the lines of force due to the inducing current, and the direction in which they must coil round the wire C D during the time they are passing it, we might predict the *direction* of the induced current in either case. It is somewhat difficult to make this clear by diagrams, but an analogy may assist us to a great extent. When any small body is dropped on the surface of still water it breaks that surface into a series of ripples which take the form of ever-widening concentric circles, as in fig. 115, where A is the point of generation. In such a manner do the lines of force spring into existence from a wire, only with far greater rapidity, and it is difficult in either case to fix a limit to their extent if the medium (the water or the ether) is not limited.

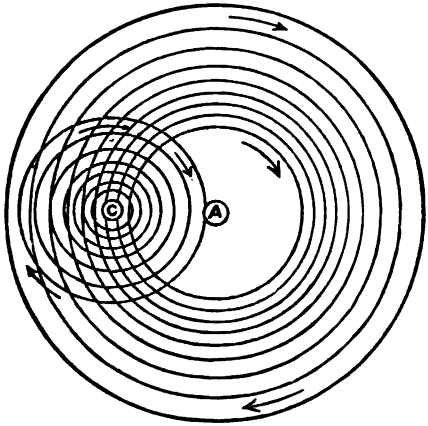
FIG. 115.



Now, if these water ripples meet any obstruction, for instance a post at the point C, they set up around it a series of circular ripples, feebler, perhaps, but precisely similar in character to themselves. It is difficult at present to say with certainty exactly what happens in the case of the electro-magnetic lines of force, but we can safely use the analogy for the purpose of demonstrating that the direction of the lines of force round the wire in which the current is induced is opposite to their direction round the inducing wire. For, suppose, as in the case of the lines of force, the original ripples round A to have what is called a positive direction—that is to say, that they circulate in a right-handed direction after the manner of the hands of a clock, as indicated by the arrows; then, since that direction would not be altered by flection at the obstacle C, they must go round C left-handedly or ntrary clock-wise. Now, if these were electro-magnetic lines of rce we know (Chapter IV.) that their direction would indicate a rrent flowing *downward* through A, and *upward* through C, and us we can readily perceive how the starting of a current in one re gives rise to an *inverse* one in a neighbouring wire. Further, see that it is only while the original ripples generated from A e *passing* the point C that these secondary ripples can be nerated or called into existence, and we may again picture to rselves how it is that a current is induced in a wire, only during e time that the current in the neighbouring wire is attaining its ll strength.

Let us now suppose it possible to cause a series of ripples collapse upon the point A, in the same manner as we imagine es of force to collapse upon a wire. Before arriving at A they uld meet with C, and, before, generate a ies of secondary rips, but in this case their ection round C and A uld be the same, for w they approach C from opposite side. Again uming the ripples to re a positive direction, arrows in fig. 116 w that their direction l be the same round h, and if A and C were es and the circles lines force, the current in h wire would be flowing downward through the paper. It s becomes easy to imagine how the stoppage of a current in a e induces in a neighbouring wire a current in the *same* direction itself. The wire in which a current is induced is called the ondary, and the one which carries the inducing current is med the primary wire.

FIG. 116.



Now, if in fig. 114 the wire A B, while carrying a steady current, were suddenly brought close to C D, or if C D were suddenly brought close to A B, the lines of force would cut C D in precisely the same manner as they did when a current was started in A B. The result would therefore be the same, that is, a momentary current would be developed by induction in C D, in the opposit direction to that of the current in A B. Furthermore, if the tw wires were then suddenly moved asunder, C D would be cut by th retreating lines of force, just as it was cut during the stopping o the dying away of the primary current, and a direct induc current would therefore be the result.

These induced currents bear a very simple ratio to the curre producing them. The E.M.F. in the secondary wire is proportio to the number of lines of force which cut it, and also to the ra at which they cut it. Now, the number of lines of force may be increased by increasing the strength of the current in the primary wire, or by adding to the length of the wires in proximity. It is, however, more convenient to wind the longer wires in spirals o helices, when the effect will be similar to that which would res from two long straight wires. It is evident that the two wi should be as close together as possible, otherwise those lines o force very near the primary wire would not reach the second wire at all, and would, therefore, fail to produce any effect there In some cases when it is desired to obtain a powerful induc current, the primary and secondary wires are wound in the fo of concentric helices, and an iron core is inserted to increase th number of lines of force which cut the secondary. Having b such means made the number of effective lines as high as possib the only other thing to be done in order to increase the second E.M.F. is to make the rate at which the secondary is cut by the lines as great as possible.

Now, supposing the two wires A B, C D (fig. 114) to lie q close together, and the current in A B to be started and to ar at its full strength instantaneously; the rate at which its lines o force cut C D would then be a maximum, and it would not b possible to further increase the E.M.F. of the induced curre except by increasing the strength of the current in A B and increasing the *number* of the lines of force. But in practice current does not rise to its full strength instantaneously, nor do stop suddenly ; time is taken for the lines of force to spring into istence and to die away, and under certain conditions this time y be considerable. To understand the principal cause of this ggishness let us refer again to fig. 115 and further study the e of the water ripples. A little thought or experiment will ke it evident that the secondary ripples round C will quickly ch the point A, and if the body which caused the disturbance still there, will set up around it ripples in the opposite sense to original ones. Now, suppose two wooden balls, A and B, were opped into the water at the same moment close together and uidistant from C, they would set up ripples round C, each to the me extent and in the same sense ; in fact, the number round C uld be doubled. But still stronger is the effect of A and B round ch other, and (still assuming a positive direction just as we do for es of force) the direction of the ripples so set up round each l be opposite to those which it generates. In the same way if rimary wire is looped into two convolutions, A and B, they l generate round an equidistant loop of the secondary just uble the number of lines of force which one will ; but they also ct upon each other, each setting up round the other, lines of force ich would generate a current tending to stop the primary one, result being that this primary current does not rise so rapidly its full strength. This retardation increases as we increase the mber of convolutions ; in fact, it varies directly as the square of number of convolutions, because each one acts upon all the ers and they in their turn act upon it. Therefore the retarda in a coil of 100 turns would be 100 times as great as in a of 10 turns.

In a precisely similar manner the reaction of adjacent convoons prevents the instantaneous *stoppage* of a current ; for, at the ment of disconnecting the battery or other current-generator, of force collapse upon each convolution, and in so doing they the other convolutions and generate a direct induced current ch will also vary as the square of the number of turns, and l to prolong, or retard the disappearance of, the primary current.

The electro-motive force resulting from this collapsing of the of force may be, and usually is, much higher than that ch maintains the original current. For, supposing the battery used consists of ten Daniell cells, then if the poles are connecte by a short piece of wire, no spark, or, at the most, a very feeble one is observable when the circuit is closed or opened quickly. I this same battery is made to send a current through a coil o many turns of wire, although its resistance may be high and caus the current to be comparatively weak, yet, on breaking the circui a spark will be observed. This is due to the fact that the lines o force fall back so quickly upon their respective convolutions i the coil, that they cut the adjacent convolutions with sufficie rapidity to generate a momentary E.M.F. high enough to produ a current sufficiently strong to volatilise a portion of the metal, an to maintain the current across the vapour-filled space for a bri interval, even after the wires are moved asunder. This effect i even more striking if in a dark room contact is broken betwe a wire and a mercury surface, when a little of the mercury i volatilised ; and, since the effect of iron placed in the vicinity i to increase the number of lines of force which are active, th spark can be increased enormously by placing a core inside th coil.

The term 'self-induction' has been given to this action, whi prevents the instantaneous rise and fall of a current, and it will evident, from what has been said, that, in the case of a sin straight wire, this phenomenon is almost imperceptible, and th in order to make the self-induction of any circuit a maximum, th wire should be wound into as many convolutions as possible, a be provided with plenty of iron.

In some cases it is desired to design electro-magnets wh shall be affected as little as possible by brief, sudden fluctuati of the magnetising current. It is manifest that in such a case t electro-magnetic inertia—that is, the self-induction—must be ma high by using a long and massive core and a great number of tu of wire ; for, as we have seen, self-induction prevents a rapid r or fall of the current, in just the same way as the 'inertia' matter prevents any instantaneous change in its motion. If, o the other hand, an electro-magnet is required to be quick-act or to be very sensitive to any variation in the current, self-induct should be as low as possible, and, in order to obtain this, the c should consist of as few turns of wire as possible, and the c ould be very short, or the turns of wire should be confined to end or ends.

The measurement of the intensity of an electro-magnetic field as already mentioned, a matter of great practical difficulty. owever, as the movement of a wire in any magnetic field tends set up a current in the wire, and as the field may be that of a rmanent magnet, or even that of the earth, and since, also, the rength of any field is proportional to the number of its lines of rce per unit area, while the current generated in a wire is also oportional to the number of lines of force cut by it, and to the te of cutting, we may compare the strength of different fields by serving the current resulting from the cutting of them by a wire equal speeds. It is advantageous to wind the wire into a small il, and place it in the field with its plane perpendicular to the rection of the lines of force, and then suddenly turn it through right angle, when its plane will be parallel to the lines of force, d none will be passing through the coil. The E.M.F. resulting ll be proportional to the number of convolutions, the strength field and the area of the coil (that is, to the number of lines of ce passing through the coil), and to the speed with which the es are removed. Special galvanometers are constructed to give values of such sudden momentary currents, by comparing which strengths of the various fields can be measured.

CHAPTER VIII.

DYNAMO-ELECTRIC MACHINES (ALTERNATE CURRENT).

IN the preceding chapters we have dealt with some of the principal laws of electric currents, and the most striking phenomena connected with them. The student will not have failed to notice two important facts : (1) That when a wire through which a current is passing is placed in a certain position in any electro-magnetic field, it has impressed upon it a definite mechanical force tending to move it into another part or out of the field ; and (2) when a conductor is mechanically moved in a field transversely to the lines of force traversing that field, a certain electro-motive force is determined, which sets up a current in the wire if its two ends are connected. Extensive use is made of both these effects in practice, and on a very large scale. Machines which are constructed to transform energy which exists in the form of electric currents into energy in the form of mechanical motion, and, conversely, machines which are able to transform energy in the form of mechanical motion into energy in the form of electric currents can be included under the generic head of 'dynamo-electric machinery.'

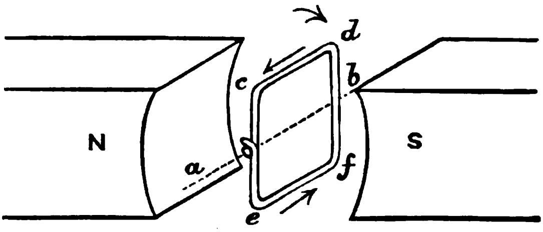
We shall first consider machines of the latter class, which are commonly known by the shorter name of 'dynamos,' deferring the consideration of the other class until an opportunity offers for dealing with such apparatus under the head of 'motors.'

In every machine for the conversion of energy, there is always a certain amount of loss attending the conversion ; in other words less energy appears in the new than existed in the original form. The more perfect the machine, the less does this loss become, so that a theoretically perfect machine would be one in which there is actually no loss at all. It is absolutely impossible to construct uch a machine, but in every case the chief aim of the engineer hould be to make the loss as small as possible, or to make the machine as 'efficient' as possible. The proper way of doing this s to start with the fact established in accordance with the doctrine of the 'conservation of energy,' that energy can never pass out of existence or be destroyed; that, therefore, the whole of the energy put into the machine reappears in some shape or form, although only a part appears in the exact state in which it is desired. Steps should then be taken to ascertain exactly what form the other part takes, and the designer of the machine should study how to reduce that same part, which may be called 'waste,' to a minimum. In all machines which have moving parts, a certain percentage of the energy takes the form of heat, due to friction at the bearings and other surfaces which come into contact. Every dynamo has moving parts, and is therefore subject to loss from this cause, and the well-known methods of reducing friction by good workmanship and design, and by the judicious use of oil or other lubricant, are taken advantage of to minimise the loss. But there are many other causes besides mechanical friction which operate to reduce the efficiency of a dynamo; they are mainly due to electro-magnetic phenomena, and careful study is required in discovering how to eliminate or minimise them, although in some instances the loss may be readily localised, because, like friction, these phenomena convert a certain amount of the original energy of mechanical motion into heat. One of the principal features, then, by which a dynamo is judged is its efficiency, or by the ratio of the energy re-appearing as electric currents to the total amount given mechanically to the machine.

We will start with the consideration of the simplest type of dynamo-electric machine, and, observing its weak points, endeavour to trace its development into a practical and highly efficient piece of apparatus.

Now, it is only during the time that the lines of force of a field are being cut by a conductor that an E.M.F. is induced in that conductor; therefore, in order to obtain a continuous current, or a very rapid succession of currents, it is evident that either the conductor or the field must be kept continually in motion. Let us first study the case of a fixed field and a moving wire, assuming, for the moment, that we have a strong and fairly uniform field produced by the opposite poles of two large permanent bar-magnets placed near to each other, or by any other convenient means. A uniform field has been already defined to be one in which the lines of force are straight, parallel, and equidistant. It is not easy to obtain a strong uniform field of any great extent, so that the most convenient way of continually cutting lines of force is to cause the conductor to move in a circular path, within the limits of a powerful field of comparatively small area. For instance, if the wire is bent into a single rectangular coil, as shown in fig. 117,

FIG. 117.



it may be placed in the field with its plane at right angles to th
direction of the lines of force, so that as many as possible of th
lines are made to pass through it. If, now, this coil is turn
suddenly through an angle of 90° about the axis *a b*, its plane is
parallel to the lines of force, and it is obvious that none of the
now pass through the coil. In the act of turning, both the t
and the bottom limbs, *c d* and *e f*, cut a certain number of lin
setting up thereby an electro-motive force in the wire; but a
these two horizontal limbs of the rectangle cut the lines fro
opposite sides, the direction of the resulting currents in them i
opposite. In the lower limb, *e f*, the direction is from front t
back, and in the upper one, *c d*, from back to front. Both curren
therefore, pass round the coil in the same direction. The si
limbs of the rectangle—that is, *c e* and *d f*—simply slide, or sl
through the lines of force, and do not *cut* them; they, therefo
have no current induced in them, and, while adding to the resi
ance of the loop, are useless, except for the purpose of completi
the electrical circuit. The student may now, with advantag

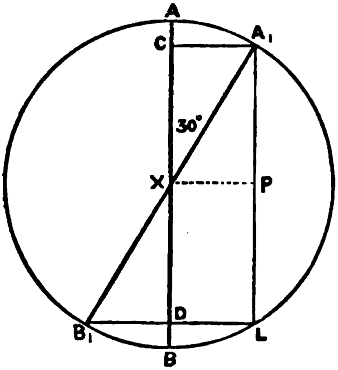
gain read the paragraph in Chapter IV. which indicates how the direction of an induced current can in every case be predicted. In the present case the lines of force go from left to right, and the number cut by each limb, so far, is half the total number originally passing through the rectangle.

When the rectangle is turned through another 90°, so that the imb which was at first uppermost is now at the bottom, it has the maximum number of lines of force suddenly thrust through it again; another induced current is the result, and as, during the movement, both the horizontal limbs cut the lines from the same side as they did in the first movement—that is to say, one limb still cuts downwards and the other still cuts upwards—the direction of the current is the same as that developed during the first quarter of a revolution. Further, as the number of lines of force cut is in each case the same, the induced E.M.F. is also the same, provided the rates of moving are equal.

If, therefore, the rectangle is rapidly turned at one sweep from its original position in fig. 117 through 180°, a current will be induced, in the direction shown by the arrows, during the whole of that movement. If the rotation is continued, on passing the 180° the horizontal limbs again begin to cut the lines of force, but they then cut them from their opposite sides, or in the opposite direction to that during the first half revolution. The resulting current is therefore in the opposite direction to the previous one, but of precisely the same strength if the motion is uniform. A continuous rapid rotation of the rectangle then, will give rise to a series of currents alternating in direction, two distinct currents being generated during each complete revolution, the reversal taking place every time the rectangle passes the points at which its plane is at right angles to the lines of force.

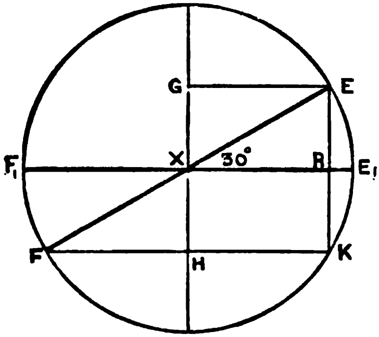
Supposing both the field and the speed of rotation to be uniform, the question arises whether the E.M.F. is also uniform during, say, the whole time of a half revolution. As the induced E.M.F. is proportional to the *rate* at which the lines of force are cut, it is only necessary, in order to decide this question, to ascertain whether the rate of cutting is, under the circumstances, also uniform. A little reflection will show that just when the rectangle begins to move from its position in fig. 117 it is *cutting* hardly any lines at all, but that its horizontal limbs, like the vertical limbs, are rather sliding along or slipping through them, and therefore at the beginning of the movement the rate of cutting, and consequently the E.M.F., is comparatively low. But when the rectangle has turned through about 90°, it is cutting the lines almost at right angles; there is practically no sliding whatever, and the rate of cutting, and therefore also the E.M.F. produced, is much greater—it is, in fact, at its maximum. This gradually decreases until, when near the 180°, the E.M.F. is again at a minimum, and the reversal takes place.

FIG. 118.



A reference to fig. 118 will make this clearer. A B represents the coil viewed end on in the vertical position; X the axis of rotation, and $A_1 B_1$ the position of the coil after it has been turned through 30°. Clearly the number of lines cut by the top limb of the coil are those enclosed in the space A C, and by the bottom limb those in the equal space B D. Therefore the total number cut during this movement of the coil may be represented by the sum of these two lines A C + B D.

FIG. 119.



Now in fig. 119, E F represents the position of the coil after it has been turned through 60°; if from this point it rotates through another 30° its position is represented by $E_1 F_1$, the lines of force cut during this movement being all those included in the space E K. Now E K is considerably greater than A C + B D, and therefore, he field is uniform, the coil cuts a much greater number of lines f force by moving through 30° when its plane is nearly parallel to he direction of the lines than it does by moving through an equal ngle while it is nearly perpendicular to them. But as the speed f rotation is uniform, it takes precisely the same time to pass hrough these equal angles, therefore the rate of cutting, and onsequently the E.M.F., must be much greater in the former than in the latter case. In fact, the rate at any moment is proportional to the *sine* of the angle through which the coil has then moved from the vertical position.

We have defined a magnetic field of unit strength to be one having one C.G.S. line of force per square centimetre, and if a conductor one centimetre in length is moved transversely through this field at a velocity of one centimetre per second, it will cut one line of force per second, and thereby develop one C.G.S. unit of electro-motive force. If either the strength of field, the velocity, or the length of wire be doubled, the resulting E.M.F. will be doubled, the number of lines cut per second being increased twofold. If we simply know the number of lines of force cut per second, the E.M.F. can be calculated without any consideration as to the length of conductor or strength of field. If the field is not uniform, however, or if the wire moves at a varying speed, the rate of cutting, and therefore the E.M.F., will fluctuate. But the *average* of this fluctuating E.M.F. will be equal to the average rate of cutting, that is to say, it can be found by dividing the whole number of lines cut by a conductor, by the time in seconds occupied in the cutting. If, therefore, the rectangle in fig. 117 makes one revolution per second, and the maximum number of lines of force embraced by it in the zero position is denoted by N, then each limb will cut 2 N lines per second, because it cuts the whole number N during the downward sweep, and again during the upward movement. Consequently each limb develops an average E.M.F. of 2 N C.G.S. units, and as both limbs are connected in series the total E.M.F. becomes 4 N units. Further, if the rectangle makes *n* revolutions per second instead of only one, then *n* times as many lines will be cut per second, and the average E.M.F. will be 4 N *n* units. But since the C.G.S. unit of electro-motive force is so very small, a much greater practical unit, called the volt, equal to 100,000,000 C.G.S. units, is employed. All results obtained in C.G.S. measure must, therefore, be divided by this number to give the value in volts, and the simple equation may be written,

$$\text{average E.M.F.} = \frac{4\,\text{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

It may be mentioned that the value of N is, in actual machines, very high, being, as a rule, several millions. In practice, it is this average E.M.F. which concerns us most, but we may observe that if the rectangle were rotated at a constant speed in a uniform field, the actual E.M.F. being developed at any moment when it had moved through an angle a from the zero position would be

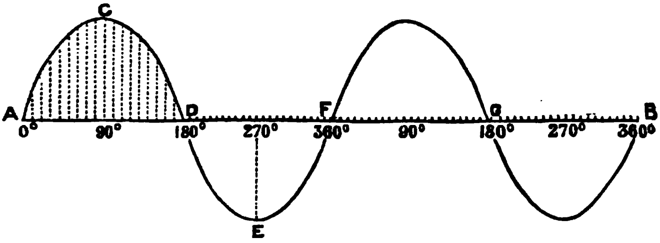
$$\text{E} = \frac{2\pi \sin a\,\text{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

The above refers to the case of two active wires, forming limbs of a rectangle and joined up in series in such a manner that the E.M.F. of one is added to that of the other. The resulting E.M.F. is twice that developed by one active limb; and if the wire were wound in a number of convolutions, it would be necessary to multiply by the number of active limbs then joined in series (instead of by 2, as in the present case) to obtain the total E.M.F.

The function above referred to as the 'sine,' is one with which the student will frequently come in contact. Perhaps, therefore, it will now be as well to explain briefly what is meant by the sine of an angle. If in one of the two straight lines which contain any angle, such as E X R in fig. 119, any point, say E, is taken, and from it a line E R is drawn perpendicular to the other line, a right-angled triangle, E X R, is formed. The length of the perpendicular E R divided by the length of the hypotenuse E X, that is, $\frac{\text{E R}}{\text{E X}}$, is a definite value, no matter what the area of the right-angled triangle may be, provided the angle E X R is unaltered. And this ratio $\frac{\text{E R}}{\text{E X}}$ is called the sine of the angle E X R. The sine of any other angle is similarly measured; for instance, in fig. 118 $\frac{\text{A}_1\text{P}}{\text{A}_1\text{X}}$ is the sine of the angle A_1 X P. If we always choose the same length of ine for the denominator, as will be the case if it forms the radius f the same or equal circles, as E X and A_1 X, and let it be equal to nity, then the sine is simply measured by the numerator E R or $_1$ P, that is, by the length of the perpendicular. When the angle ecomes very small, the perpendicular, and therefore the value of he sine also, becomes very small; in the case of the imaginary ngle 0° the perpendicular disappears, the sine of 0° being 0. When the angle is 90° the perpendicular coincides with and is equal to the radius. The sine of 90° is therefore 1, and this is the highest possible value of the sine. It decreases as the angle further increases, until, at 180°, its value is again 0. From here it is reckoned as negative, the sine of 270 being — 1. By referring to a table such as that on p. 98 the value of the sine of any angle can readily be found, and we can, therefore, calculate the relative value of the E.M.F. at any position of the rectangle, and also show diagramatically how the E.M.F. should rise and fall in a perfectly uniform field.

In fig. 120 the portion A F of the horizontal line A B represents a circle straightened out, each of the four equal parts into which it

FIG. 120.



(A F) is divided being equivalent to 90°, that is, a quarter of a revolution of the rectangle. Similarly, this line A F might be subdivided into 360 parts to represent the 360 degrees, and any point along it could then be taken to denote the position of the rectangle when turned through a corresponding angle from zero. Now we have observed that the E.M.F. at any point is proportional to the sine of the angle through which the coil has then turned from zero; and it is convenient to take a number of points along this line, and at each of them erect a perpendicular proportional in length to the sine of the angle which that particular point represents. During that half of the revolution in which the sines are reckoned as minus, the perpendiculars should be drawn below the line, indicating the reverse direction of the E.M.F. and current. For instance, at 90° the sine will have the greatest value, viz. unity, while at 45° the perpendicular will be only 0·707 of that at 90°, because the sine of 45° is 0·707 ; at 270° the sine is − 1, and therefore the perpendicular equal in length to unity is drawn below the line.

By joining the extremities of these perpendiculars we obtain a curve known as a sine curve, which at a glance indicates the manner in which the E.M.F. rises and falls during one complete revolution of a simple coil ; and the whole of the curve from A to B shows the fluctuation of the E.M.F. during two revolutions.

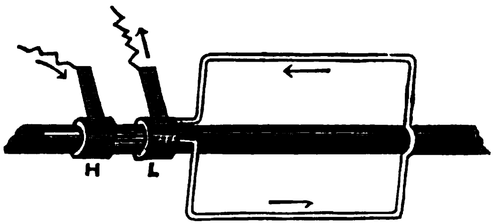
If in fig. 119, EX is taken as unity, it may represent the height of C or E, the highest points on the sine curve, and then EG will be the length of the perpendicular representing the electro-motive force at 60°, for EG is the sine of the angle EXG, which is the angle (60°) through which the coil has turned from the vertical position. Similarly, A_1C (fig. 118) will represent the E.M.F. developed when the coil has turned through 30°, for A_1C is the sine of that angle.

The curve (fig. 120) shows that the E.M.F. at 90° is equal to that at 270°, but that it is positive in the one case and negative in the other.

Referring again to figs. 118 and 119, we observe that the 'effective area' of the coil, with respect to the lines of force which it embraces in the position A_1B_1, is proportional to A_1L, and in the position EF to EK—that is, A_1L and EK are proportional to the number of lines of force passing through the coil in the two positions. Now, $\frac{A_1L}{A_1B_1}$ is the cosine of the angle through which the coil has already rotated, for the angles A_1XA and PA_1X are equal, or it is the sine of the angle which the coil makes with the direction of the lines of force ; as is also $\frac{EK}{EF}$. Taking, for simplicity, the equal lengths A_1B_1 and EF as unity, we see that the number of lines of force passing through the coil in any position ı uniform field is proportional to the cosine of the angle through ich it has been turned from its position at right angles to those s, and also to the sine of the angle which it makes with the s of force.

These variable alternating currents, depicted in fig. 120, being s developed by the rotation of the wire rectangle, some device equired to enable us to lead them away to an external circuit l there make use of them. The rectangle might, for this pur- e, be mounted on a wooden spindle (fig. 121), and its ends mected to two : metal rings, , fixed a little tance apart on : spindle, con- t being then de by means of at spring, or a : brush, press- against each of rings. By attaching wires to these contact brushes the currents be conducted away to any desired point.

FIG. 121.



It remains now to show to what extent, in practice, we can ply with the conditions which theory teaches us will tend to e the E.M.F. high.

For a small machine, permanent magnets may be used to ply the field, and for this purpose a horse-shoe magnet is found e very convenient, but it should be bored out or fitted with iron cheeks, of such a shape that there is just sufficient room the wire coil to rotate between them. The steel should be ngly magnetised, and, if of considerable size, it should be inated, or built up, of a number of these magnets with their poles adjacent. A circular magnet (fig. 122), divided at one of the circle, and with just sufficient space bored out for the to rotate, is better than one of the ordinary horse-shoe pattern, ough not so easy to make. Having obtained the magnetic l, the next thing is to get as many as possible of the lines of e to pass through the coil of wire. Iron here comes to our stance once more, for, by winding the rectangle round a core of pure soft iron, we concentrate those lines which would otherwi stray, and the number passing through the wire is greatly increase It is almost superfluous to add that the actual area of the rectang should be as great as possible, provided that it is kept within t limits of the field, and since, as we have seen, the induced E.M. is proportional to the number of active conductors joined in serie the wire may be wound into a coil consisting of a number of tur instead of only one. Now, a c in which currents are induced b its movement within a magneti field is generally called an 'arma ture.' The core of one of th earliest forms of armature is shown in section at A, between the pole of the circular magnet F, in fig. 122, and although, when criticised in the light of our present knowledge, the design proves to be very faulty, it will serve very well to illustrate the principle. A view of this armature is also shown in fig. 123. It consists of a considerable length of silk- or cotton-covered copper wire, wound in the grooves of a shuttle-shaped piece of soft iron, A B, which is usually about twice as long as its greatest width. It is provided at one end with a driving-pulley, *p*, and at the other end by a device for communicating the current to the external circuit. Good effects can be obtained by rotating such an armature in a strong field. The speed of rotation must be high, but this can readily be obtained by any mechanical multiplying device, such as a pulley of large diameter driving a smaller one on the armature spindle. Although the E.M.F. increases with the number of turns of wire on the armature, it is found that this increase is not by any means proportional,

FIG. 122.

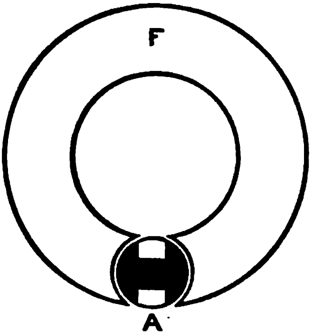
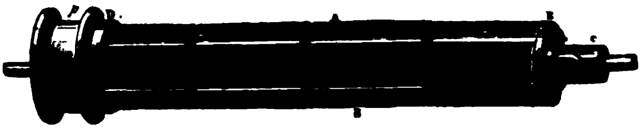


FIG. 123.



ecially when the speed of rotation becomes very high. One portant reason is because the conditions are very favourable for 'self-induction' of the armature to make itself evident. We re already seen that this effect becomes very marked with idly varying or alternating currents, and since, also, it increases h the square of the number of turns of wire, it is obvious that number cannot be indefinitely increased with any prospect of isfactory results. The increase of resistance, though not in lf such an important matter, also limits the length of the wire. is, therefore, preferable to endeavour to increase the strength of field and the length of the active limbs of the coil rather than number of turns.

That the design of the shuttle armature is faulty may easily be ved, for, after being rotated for a little time, the iron shuttle or e gets quite warm. Now, this heat, so developed, represents a nite fraction of the energy expended in rotating the armature, ch, as it does not reappear as electricity, is to all intents and poses wasted. It is an interesting fact that whenever a mass metal is rapidly rotated in a magnetic field its temperature rises, heat being the direct result of currents of electricity which are ced in the metal, and which are known as 'eddy' currents. ir initial direction is at right angles to the lines of force of the netic field, and also at right angles to the direction in which mass moves; therefore, in the shuttle armature, they travel thways along the iron core, completing their circuit in a more ess circular path in the iron (whence they gain the name of dy' currents), and they follow the general law in reacting upon field in which they are produced, in such a manner as to tend top the motion of the moving body. The E.M.F. of these ents is not high, but as the mass of the metal is great, and its tance therefore small, the currents are sufficiently strong to iderably raise the temperature of the metal. In fact, it is ble to melt a piece of a metal which fuses at a low tempera- by simply spinning it rapidly in a very strong field.

t is evident that such a certain sign as this, that energy is g wasted, must not be ignored, and, since we cannot stop the ency for the currents to be produced, the only alternative is to difficulties in the way of their production.

In the case in question, the best method is to 'laminate' th armature, or to build it up with a number of small discs cut to th required shape and bolted together, instead of using a solid pie of iron. The iron must be continuous in the direction in whi the lines of force have to pass through it, otherwise the efficacy o its action in concentrating these lines would be seriously impair while it must be discontinuous in the direction in which the ed currents tend to flow, viz. at right angles to the lines of force. T meet these requirements the discs threaded on the spindle mu be well insulated one from another, although, on account of th low E.M.F., a sheet of thin paper or a layer of varnish is, as a ru sufficient. It is hardly necessary to adopt this precaution in t kind of machine we have been considering, which is very sm and only made to be driven by hand-power, but it becomes ab lutely necessary, as well as economical, in the larger machi driven by steam-power. At first sight it would appear, rememb ing that the E.M.F. developed in the armature coil varies as t rate at which the lines of force are cut, that the E.M.F. of a m neto-electric machine should be simply proportional to the sp of rotation, the strength of the field being invariable. But th are several causes which tend to prevent the increase of the E. developed by the augmentation of speed attaining this proporti the principal being the eddy currents produced in the core, t electro-magnetic reaction of the current in the armature upon t field produced by the field-magnets, and the self-induction of t armature. It is important to notice that when a current is flo round the armature coil the whole armature is in reality an elec magnet, and it acts as such upon the poles of the perman horse-shoe magnet which supplies the field, this reaction, as i every similar case, tending to stop the motion of the armat If, however, the armature is forcibly rotated against this tende the result is that the magnetic field is distorted and dragged so what out of its true position, and, as the current in the arma rapidly alternates from zero to a maximum, this dragging eff will also vary considerably, with the result that the field will kept in a state of oscillation and its uniformity destroyed. T maximum current in the armature becomes higher as the speed increased, and the distortion of the field is then greater, the res g a tendency to prevent the E.M.F. rising in proportion to the d. Furthermore, as the iron core has a greater number of s of force passing through it when the current increases, its neability may also become appreciably lower.

Besides the waste due to eddy currents, which increases very dly with the speed, the effect of the self-induction of the arma- also becomes strongly marked, this latter not only preventing a high E.M.F. being attained, but, in addition, retarding the and fall of the current. In fact, were we able to plot a curve wing the rise and fall of a current in this shuttle armature, we ld find it somewhat similar to that given in fig. 120, but with important difference that it would be shifted more or less to right, its maxima and minima being less in value and occurring r than would be the case if the armature had little or no self- ction. Owing to the fact that it is not possible to construct actical armature with as little self-induction as the simple angle, or to make its active limbs cut the lines of force of a orm field in such a regular manner as is done by our experi- tal rectangle, we do not in practice obtain a perfect sine curve the curve of potentials of any armature, but only an approxima- thereto.

We shall presently be better able to consider the reaction on field in connection with a different type of armature, but we here remark that it is one of the most important points to be e in mind in deciding how a more powerful and efficient hine can be obtained. Now, the electro-motive force may be eased in several ways.

1. By increasing the speed of rotation.

2. By increasing the number of turns of wire in the armature, increasing the number of active limbs joined in series, which the lines of force. This method, as already pointed out, adds only to the resistance, but also to the self-induction of the ature.

3. By increasing the area of the armature coils, or by making core more massive, for in either case the number of lines of e cut by the coil is, within certain limits, increased.

4. By increasing the strength of the field.

The last-named method is the freest from objections, and it has the all-important advantage that, the stronger the fixed field i as compared with that developed by the armature, the less is th reaction and consequent distortion of the field.

The necessity for a strong field is so apparent that powerf electro-magnets are now usually employed, but, as might b expected, in all the early efforts to construct a dynamo-electr machine, the field was obtained by means of permanent magne But the method of cutting the 'armature' wires by lines of fo was not by any means restricted to the rotation of the armature i the field. One very interesting method was applied by Whe stone, and is still largely employed, to ge rate short intermittent and comparati feeble currents. The wire in which the c rents are generated is wound on, let us s two bobbins (see fig. 124), which are fi with soft iron cores, as shown by the d lines, and placed one on each pole of a po ful permanent steel magnet. Many of t lines of force due to this steel magnet p through the soft iron cores, and comple magnetic circuit across the air-space at the top in the well-kn curved form, but no current is generated in the wire while are undisturbed. If, however, a soft iron bar is placed across ends of the cores and very near them, as shown in fig. 124, or as sh by the dotted lines in fig. 125, a g many of the lines of force rearr themselves and pass through this iron 'keeper.' In moving to their positions they cut the convolution the coil and generate therein an ele motive force which, if the circuit is c pleted, gives rise to a momentary current. When the keep entirely removed the original arrangement is re-established, the cutting which then takes place also generates a mome current, but in the opposite direction to the previous one. most convenient way of rapidly shifting the soft iron keeper i mount it on a spindle and rotate it; in fig. 125 it is shown at

FIG. 124.

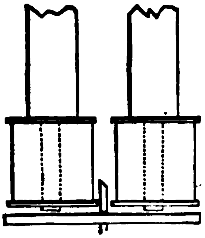
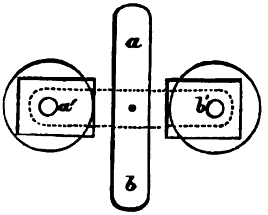


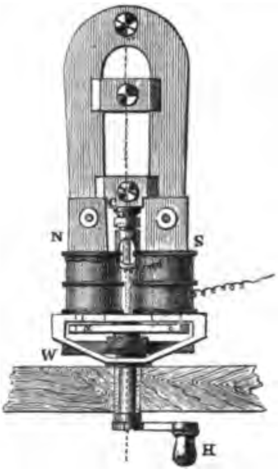
FIG. 125.



the position at right angles to the line between the two bobbins, ile the dotted lines show its other extreme position, a^1 b^1, when is right over the cores.

In fig. 126, which is a view of a portion of the actual apparatus, s keeper *a b* is shown fixed on a spindle, which also carries a ion gearing into a larger driving-wheel, W, turned by a handle, H. e keeper can, by means of this arrangement, be rotated with siderable velocity in front of the two bobbins, which, with their es, are shown fixed to the soft iron cheeks screwed on to the les of the horse-shoe magnet N S, ich is a compound one, being built of seven thin horse-shoes bolted ether. Four coils are usually emyed, placed symmetrically, two on ch pole; double the number of rents in each revolution are then nerated, but the principle remains e same.

FIG. 126.

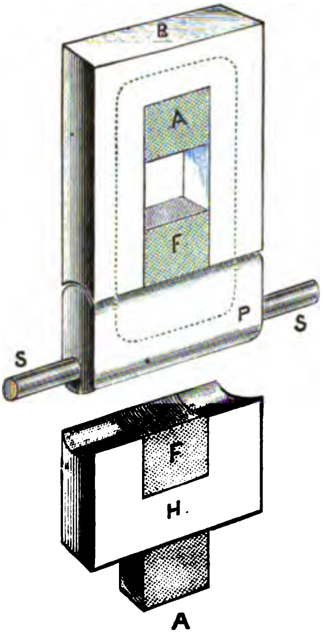


Hitherto no large machines built pon the foregoing principle have been actically used, and this is, perhaps, rprising, as the advantages due to e simplicity of construction are many d important. The only moving rt of the apparatus is a mass of iron hich, if truly balanced, can be rotated a very high speed without involving y mechanical difficulties, and as all the coils are fixed, connection between them and any external circuit can easily be made. Mr. W. M. Mordey has, however, described several methods of applying this principle to large machines, and he has constructed a model of one form which certainly appears to be charmingly simple and practical.

The armature and field coils are each wound in the form of a ring of rectangular section, the former being of larger diameter than the latter, and they are placed concentrically, with the field coil inside the armature coil. A number of pieces of iron are placed in such a manner that the rotation of an iron keeper causes many of the lines of force at one moment to embrace both armature and field coils, and at the next moment to pass round the field coil only; and as, during their movement from one position to the other, they cut the armature coil transversely, alternating currents are induced in that coil.

The principle may be more easily grasped by a consideration the arrangement illustrated in fig. 127, in which F F show the fiel coil in section at two points opposite extremities of a diamet and A A show sections throu two similar points of the armat coil. B is a mass of iron whic embraces both the armature field coils, while H is a piec equal in cross-section but hav shorter limbs, which embraces field coil only, the armature being placed outside the P is a keeper carried by the sh S, which can be rotated rap the shaft being at the cente the two circular coils, F F and If a powerful current is through the field coil F F, a number of lines of force will developed, and their arrange will largely depend upon the pieces, H and B, but more e cially upon the position of keeper P with respect to H an

FIG. 127.

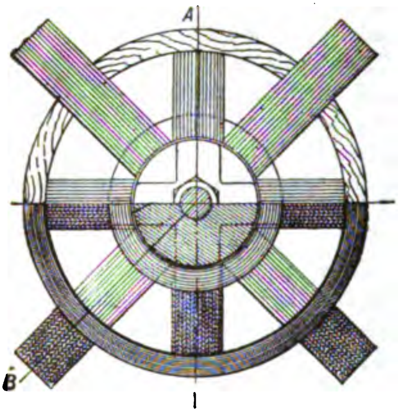


When P is situated as shown in the figure it forms with almost complete magnetic circuit of low permeability round coils A and F, and nearly the whole of the lines generated by field coil in the vicinity will embrace the armature. In sprin into this position (shown by the dotted line), the lines cut armature coil transversely from the inner side, and give rise current, depending in E.M.F. upon the number of lines and rapidity with which their position is changed. When the ke moved away there is a considerable air gap, offering a high magetic resistance at the ends of the limbs of B, and consequently any of the lines of force collapse upon the coil F, cutting the mature from the outside and generating an E.M.F. in the opposite irection. Not only is the magnetic resistance of the path round the wo coils made greater, but as P rotates it reaches a position where it cts as a keeper to the iron piece H, which embraces the field coil nly, so that an almost complete magnetic circuit is then formed ound the field coil, and nearly the whole of the lines of force pass through H and P and very few extend round A. Therefore, if the keeper P is rapidly rotated the armature coil will be cut by a number of lines of force as they take up new positions, first outside and then inside it. It is evident, however, that it would not be possible to make all the lines of force developed by the field coil take either the one path or the other, many of those surrounding the coil at a distance from the iron being but little affected by the movement of the keeper, but in designing an actual machine care would be taken to so dispose the iron that most of the lines of force would be influenced.

In Mr. Mordey's machine there are four iron pieces similar to B, embracing both armature and field coils, placed 90° from each other as shown in fig. 128. Between these are placed four shorter pieces similar to H, outside the field but inside the armature wire.

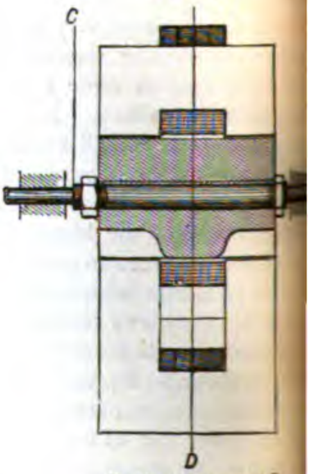
The lower half of fig. 128 is shown in section; fig. 129 is also in section, the upper half from A to the centre of the shaft, and the lower half from the centre of the shaft to B, so as to obtain a section through a short and a long iron limb. The mass of castiron which plays the part of a keeper may be described as a cylinder having four deep sector-shaped notches cut at each end. If viewed end-on, a section near one extremity would be in the form of a cross, while a section through the middle would be circular. In the figures each arm of the cross is shown as forming a keeper to one of the smaller iron pieces embracing the inner or field coil only, and consequently few of the lines developed by the field coil extend round the armature coil. In the lower part of fig. 129 the deep notches are opposite the iron pieces which embrace both coils, forming a great break in the magnetic circuit, and this is also shown in fig. 128. On rotating through an angle of 45°, however, the keeper completes the various magnetic circuits in such a manner that most of the lines of force extend round both coils. These two alternate conditions succeed one another rapidly as the keeper continuously revolves. As the lines of force are rapidly carried backward and forward past the armature coil, they generate therein the desired currents, but they also give rise to eddy currents in the masses of iron through which they are projected. The direction in which these eddy currents would be set up is parallel to the currents in the armature coils, and therefore the masses of iron should be laminated so as to give discontinuity in this direction, while continuity is retained in the path of the lines of force. Consequently the iron is built up of a number of thin U-shaped sheets, insulated and bolted together.

FIG. 128.



Section through C D.

FIG. 129.



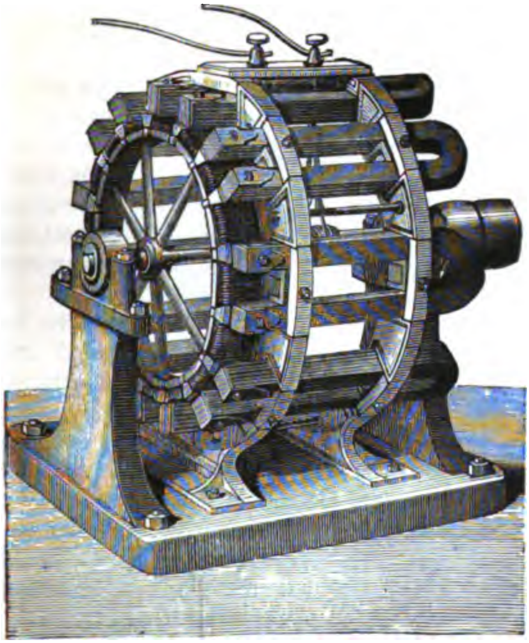
Section through A B.

Machines in which steel magnets are employed for producing the field are often called magneto-electric generators, and are sometimes regarded as a class altogether distinct from machines in which the field is developed by one or more electro-magnets, but such a distinction is altogether arbitrary.

The best and most useful form of so-called magneto-dynamos that of De Meritens, which is extensively employed for lighthouse urposes. A general view of a simple form of this machine is hown in fig. 130.

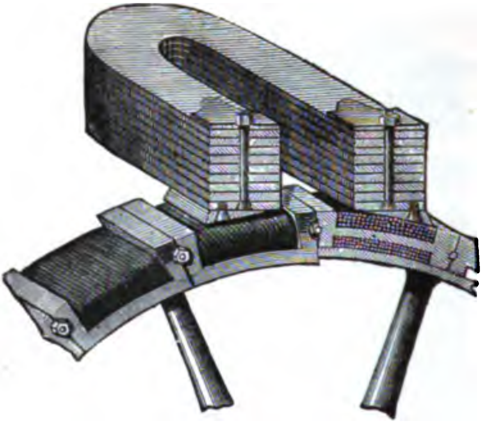
The armature consists of a series of sixteen coils fixed round he periphery of a wheel of brass or other non-magnetic material.

FIG. 130.



The method of constructing and fixing the coils is shown in fig. 131, one coil and a portion of the rim of the wheel being in section. A flat core of soft iron (composed in the more recently built machines of eighty pieces of soft sheet iron one millimetre thick and stamped out to shape) is provided with rather large pole-pieces, and has wound over it about 1½ pounds of copper wire. Each coil is distinct from the others, the cores of two adjacent coils being magnetically insulated (at X Y, fig. 132) by a thin strip of copper. The wheel or frame to which the coils are attached is furnished with a number of substantial lugs. The ends of the pole pieces of the cores are placed between these lugs, and, being provided with semi-cylindrical grooves of the necessary dimensions, the whole are firmly fastened together by bolts. It is important to notice that the extensions of the cores reduce the air-space between the poles of the permanent magnets and the cores to a minimum, and therefore conduce to the projection of the highest possible number of lines of force through the coils and consequently to the generation of the maximum attainable E.M.F.

FIG. 131.



The field is produced by a series of eight compound steel magnets fixed horizontally round the armature ring, by means of a brass framework. The inner surfaces of the magnets are provided with small soft iron pole-pieces, so that the coils in revolving pass as close to the field-magnets as possible. The magnets are disposed uniformly round the ring, the coils passing, therefore, north and south poles alternately.

The distance between the limbs of each magnet being exactly equal to that between the opposite poles of the adjacent magnets, and this distance being also equal to the length of each coil, it follows that, on the armature being rotated, each coil passes sixteen alternate poles in one revolution. The manner in which the currents are induced can best be appreciated by a reference to fig. 132, where the ring has only four coils which rotate between a similar number of magnet poles, N S N S, one coil or segment, A B, being shown in section. When the coils are in the position shown, the minimum number of lines of force is, at that moment, passing through them, but after traversing another 45°, the core-extensions will be opposite the field-magnet poles, and the coils will then embrace the maximum number of lines of force; at this latter point the reversal of the current takes place. The coils being all wound in the same direction and all connected together in series, it is evident that the current in the adjacent coils will be opposite in direction to that taken by the current in A B, as they are passing through fields developed by the south poles. Were the adjacent ends of the neighbouring coils connected together, the currents in the various coils would therefore neutralise each other and no electricity could be urged through the external circuit. This difficulty, however, can be very readily obviated, as will be made evident by a reference to fig. 133. Instead of connecting the adjacent ends of two coils together, the connection is made between their two similar ends, that is to say, the end of the coil A to the left hand is connected to the similar end of B, while the end of B to the right hand is connected to the right-hand end of C, and so on. In this way, although the currents in the various coils are generated in opposite directions, they, instead of neutralising one another, are made to take one common direction through the circuit. This does not, of course, alter the fact that the current delivered by the dynamo is an alternating one, that is to say, as the coils advance from one set of magnet poles to the next, the direction of the current in the whole of the coils is reversed, and therefore, also, the direction of the

FIG. 132.

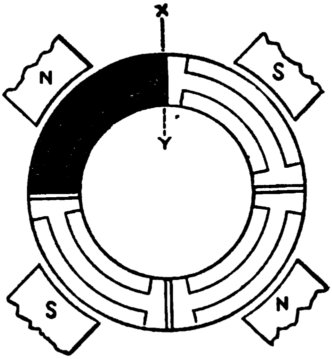
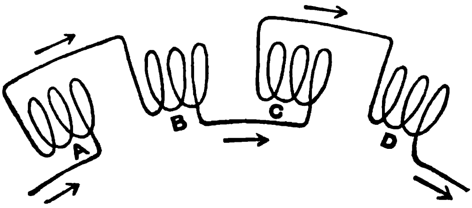


FIG. 133.



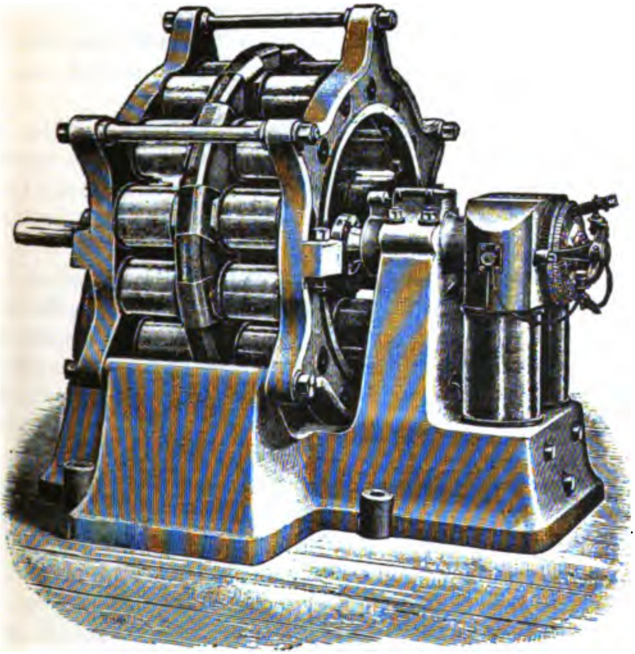
current in the external circuit. The whole of the coils in fig. 130 being joined together in series, the total E.M.F. developed is sixteen times that developed in one of the coils. In the more recent form of this machine there are five armature rings, each with its sixteen coils and eight compound magnets. The latter are, for very apparent mechanical reasons, fixed radially instead of longitudinally, and they have a total weight of about one ton. The eighty coils are divided into two circuits which are brought to four collecting rings mounted in pairs on an insulating bush fixed on the principal shaft of the machine and, therefore, revolving with it. This type is almost exclusively employed for lighthouse purposes, and its E.M.F. varies almost directly with the speed of rotation. It is unusually strong in design, the parts being also fixed together in such a manner as to permit of their being, when defective or injured, very easily removed for renewal or repair.

It has been pointed out that the best means available for increasing the E.M.F. and therefore, also, the strength of the current yielded by a machine, is to increase the strength of the field. Now there is a limit, which is soon reached, to the field obtainable with permanent steel magnets even if built up of thin sections, because the maximum number of lines of force which can be urged through steel is comparatively low, and even then only a portion of this number can be permanently retained, whereas with good soft iron a far greater number can be forced through. If the lines of force are produced by a current circulating in a coil of wire enveloping the iron, the question of retentivity does not arise. Consequently, to develop a given amount of power, a machine in which the field is produced by electro-magnets is considerably smaller than one in which steel magnets are employed.

Primary batteries might be, and in fact were at one time, used to furnish the current for the purpose of exciting the field-magne but it is far more economical and advantageous to obtain th current by means of a small dynamo. This auxiliary machi which we will for the present refer to as the exciter, must be ab to excite itself and to yield a current continuous in directi Descriptions of many such dynamos will be found in the follow chapters.

We can scarcely do better, in commencing a study of th modern forms of alternating machines, than describe one which would appear to follow as a natural evolution of the De Meritens. Such a machine, excellent alike in its mechanical and its electrical details, is the one designed by Mr. Gisbert Kapp, and illustrated in fig. 134, which also shows the small exciter mounted on an extension of the main bed-plate, its armature being also fixed on to the main shaft. The field is produced by two crowns ot short cylindrical electro-magnets, the cores of which are of wrought-iron $4\frac{1}{8}$ inches in diameter, fixed at one end into cast-iron yoke rings, and provided at their inner ends with rectangular pole-faces, between which the armature revolves. There are twenty-eight of these magnets, fourteen in each crown. Each magnet is wound with 186 turns of thick insulated copper wire, the whole of the

FIG. 134.



coils being joined in series and offering a total resistance of 176 ohms. The winding of these coils is such that the magnets forming each of the crowns alternate in polarity, while the opposing faces are of the same polarity. One continuous core is used for the whole of the coils in the armature, and is built up by winding thin band-iron upon a cast-iron supporting ring, the layers being insulated by varnish to prevent the flow of eddy currents. The section of this core is almost rectangular, with its greater dimension radial. The armature wire offers a resistance of 1 ohms, and is divided into fourteen coils, wound over the core ring, each coil consisting of eighty turns of insulated wire 120 mils (0·12 inch) in diameter, wound in two layers.

The manner in which the currents are generated as the armature rapidly revolves through the alternate fields is very similar to the method of production in the De Meritens machine. In this case, however, the lines of force enter the armature at both sides of the flat ring instead of at one side only.

The extremities of the armature wire are connected to a p of brass rings on the shaft, from which the current is collected b copper brushes. As the E.M.F. of these machines is usually hig it is a frequent practice to place the collector-rings on oppo sides of the armature, so that the attendant cannot touch bo brushes at the same time.

The machine illustrated is one constructed within the last fe months. Before being put into practical use a number of experiments were performed to ascertain its capabilities. On o occasion it was driven at 600 revolutions per minute, and, th exciting current being 9 amperes, the total E.M.F. developed o open circuit was 1,000 volts. When the exciting current w increased to 21 amperes the E.M.F. rose to 2,400 volts. With th same exciting current and the armature of the alternator join through an external resistance and a dynamometer, a current o 30 amperes was generated, the E.M.F. at the terminals then bei 2,000 volts. The available output was therefore 60,000 wa The power absorbed in exciting the field-magnets was 775 wa or about 1·3 per cent. of the total output, the loss in the arma due to its resistance being 2·7 per cent.

The cast-iron bed-plate is very substantial, and the method o olting the yoke-rings to it and to each other is clearly shown in e illustration.

When all the coils are joined in series, the total E.M.F. at the ollecting brushes is equal to that developed by one coil multiplied y the number of coils, but occasionally, in such machines, a ower E.M.F. with a heavier current is desired, and then the coils re joined in parallel, either in two sets, or as may be required. n equal E.M.F. might, of course, be obtained with fewer coils and ole-pieces, provided the number of lines cut in the same time nd the number of convolutions in series is made the same; but he great advantage accruing to the use of a large number of pole-pieces and coils is that a rapidly alternating current can be obtained without rotating the armature at an enormous speed, and so introducing mechanical difficulties.

It ought perhaps to be explained here that the current, or rather currents, resulting from one complete rotation of a coil in a simple field, which may be represented by the curve A C E F in fig. 120, is called an 'alternation,' and any similar pair of currents developed by any armature with any field is also called an alternation. In estimating the rapidity with which a current is reversed, it is better to speak of the number of such alternations which take place in a second, rather than the number of reversals. The majority of the machines at present in use work at from 80 to 100 alternations per second, and to obtain the latter number a single coil in a single field would have to be driven at 6,000 revolutions a minute. But although a rapidly alternating current can be easily obtained with a large number of pole-pieces, a disadvantage results from the fact that these pole-pieces alternate in polarity all round each crown. Each pole-piece is flanked on either side by others of opposite polarity, and a very large percentage of the lines of force leak across between adjacent limbs, instead of passing through the armature core, and are wasted, since they cannot be cut by the conductor. This defect also exists in the two machines next to be described, where the armature contains no iron.

The form of alternating current dynamo constructed by Siemens is illustrated, together with its exciter, which is driven, independently, from the main shaft, in fig. 135. The field-magnets present an appearance similar to that of those in the Kapp machine, consisting, as they do, of two opposing crowns of cylindrical electro magnets, but with the essential difference in the winding that the

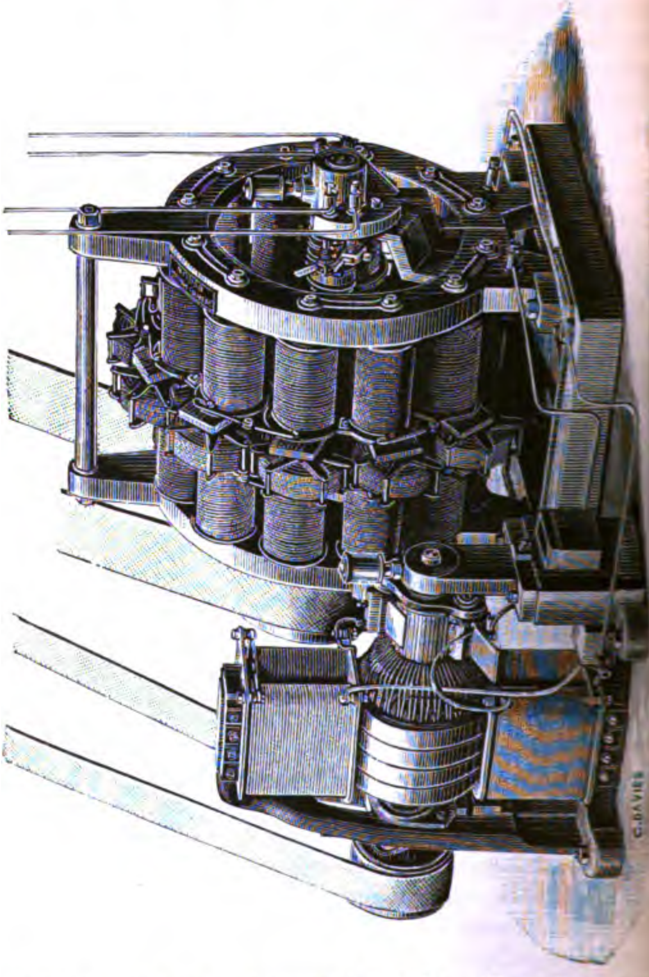
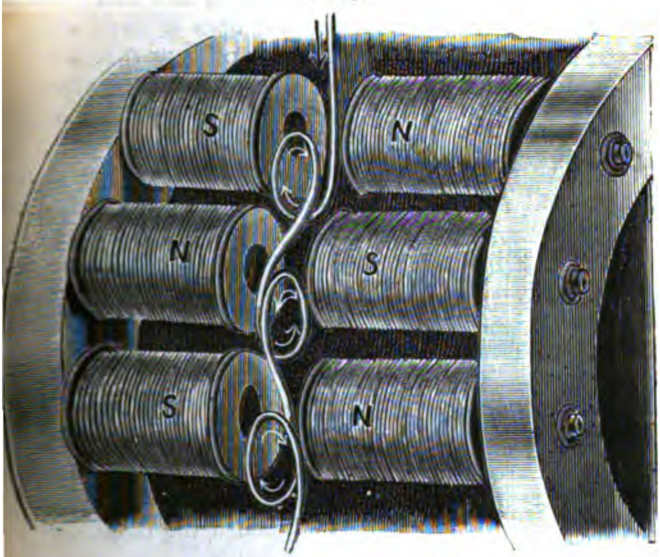


FIG. 135.

facing pole-pieces are of opposite polarity. The adjacent pole-pieces on each frame resemble the Kapp in being also of opposi arity. The arrangement is clearly indicated in fig. 136, which ws three pairs of magnets and three ideal armature coils, and it l be evident that, with this disposition, the lines of force pass m pole to pole, straight across the armature space. The plane the armature coils is coincident with the plane of rotation, so that coils, in rotating, cut through a series of powerful fields with lines of force alternating in direction. As through any adjacent r of coils the direction of the lines of force is opposite, it is

FIG. 136.



essary, in order to prevent the current induced in one coil neutral-g that induced in the other, either to make the connections as he case of the De Meritens (fig. 133), or to wind the bobbins as nt- and left-handed helices alternately, after the manner shown ig. 136. The number of armature coils being the same as the nber of fields, it follows that all these coils are, at any particular ment, equally active. Referring to fig. 136, in which the ction of rotation is left-handed, it will be seen that the coils just leaving the pole-pieces, and currents are being gene rated in the directions indicated by the small arrows. The E.M.F. increases until the coils arrive at positions midway between the pole-pieces, where it is a maximum, because at that moment the forward half of each coil is cutting lines of force in one directio and the rear half in the other direction. And the induced cu rents, flowing outwards in one half and inwards in the othe coincide in direction round the coil. Every line of force then c by the coil is being usefully employed. When this middle positi is passed, the number of lines cut by the front half increases, whi the number cut by the rear half decreases, and this continu until both halves of the coil are cutting lines of force which a all in one direction. Consequently, an opposing E.M.F. is induced in the rear half, the value of which increases until the coil i exactly opposite the pole-pieces, when both halves will be cutti an equal number of lines of force, which are all in the same direc tion; whence equal and opposite E.M.F.'s will be induced in the two halves of the coil, thus neutralising each other. At this poi then, the reversal in the direction of the current takes place, in on passing forward, the front half of each coil is cutting le instead of more, lines of force than the rear half. The number alternations in each revolution corresponds, therefore, with th number of coils, or, what is the same thing, with the number fields.

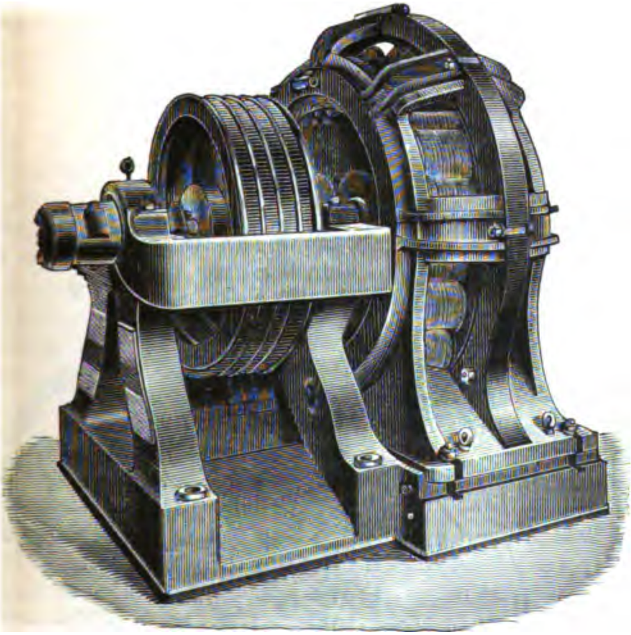
In practice, the machine is built up on a cast-iron bed-pl to which are securely fixed two circular frames, united and h in position by a stout iron stay. An equal and even number electro-magnets is fixed to each frame, the cores being tu down so as to fit into holes drilled through the frames. Th ends are likewise tapped, and, nuts being screwed on on outside, the electro-magnets are fixed firmly in position. Th inner ends of the cores are furnished with radial pole-pieces, concentrate the fields and increase the number of lines of fo passing through the rotating armature coils.

The armature is fitted up by attaching the coils, which wound over wooden cores, round the circumference of a dis wheel which is mounted on the shaft. The coils, instead of be circular, like those in fig. 136, are pear-shaped.

A general view of the latest form of machine designed by

Z. de Ferranti, is given in fig. 137, the particular one illustrated ng constructed to develop 150 electrical horse-power. The field-gnets are similar in principle to those in the Siemens Alternator, d consist of two sets of electro-magnets, attached to massive iron gs forming the yokes, the magnetisation of the pole-pieces round h ring being alternately north and south, and the facing pole-ces also of opposite polarity, so as to develop a series of very power-ul fields, alternating in direction. The framework carrying each rown, or ring, of field-magnets is divided vertically into two halves, which, on being unbolted, can be slid out of position in a direction at right angles to the shaft, and so afford access to the interior for cleaning or repair. It may be mentioned that in larger machines at Deptford a small steam-engine is specially provided for the pur-pose of withdrawing the field-magnets when necessary.

FIG. 137.

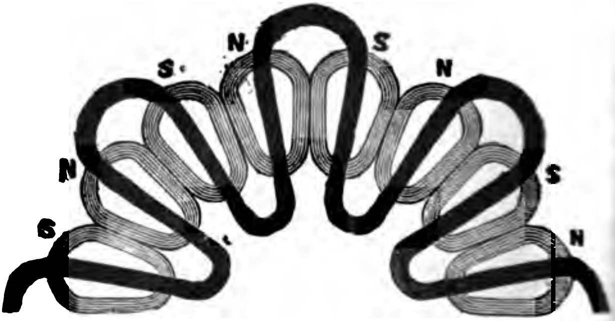


The machine is driven by rope gearing, the pulley bei grooved for the purpose.

The method of securing the cores of the magnets to the yoke-rings is unique. The wrought-iron cores of half the magnets forming each crown are fixed in a mould, and the half of the yoke-ring is then cast on to them, making in that way the surest and simplest form of magnetic connection between the wrought and cast-iron sections of the field-magnets.

The great feature of the original Ferranti machine consisted in the construction of the armature, which is illustrated in fig. 138. The heavy zigzag line represents half of the armature

FIG. 138.



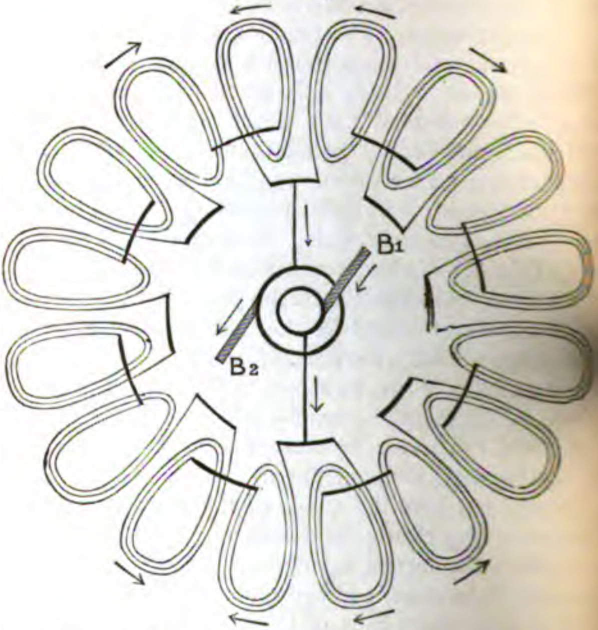
which consists of a copper ribbon bent round and bolted to non-magnetic framework attached to the shaft. The faces of o set of field-magnets are shown behind the armature strip, and will be seen that the space occupied by each complete bend in the armature is equal to that of two field-magnet coils, the distance between two straight radial portions being equal to the width one coil. When the armature is rotated all the radial portions the strip are usefully employed in developing E.M.F. At a particular moment each of these portions is cutting lines of fo in a direction reverse to that of its immediate neighbour. Consequently, opposite currents are generated in adjacent radial portions, but the zigzag winding naturally makes all the simultaneously generated currents travel round the armature in a common direction.

Alternate current machines being usually required to develop igh electro-motive force, such a simple winding is of little ser- e, although it answers the purpose admirably when only a low ctro-motive force is required. The E.M.F. developed is, of rse, proportional to the actual number of the straight radial tions of the armature wire which cut the lines of force trans- sely. It is manifest that to greatly increase this number in a ple zigzag form would be impracticable, from the fact that the nber of field-magnet bobbins must always be twice that of the ps in the armature. The practice, therefore, is to coil the per ribbon several times round a number of non-magnetic, r-shaped bobbins. Then, if the whole of the bobbins are con- ted in series, the total E.M.F. developed will be equal to the .F. of one multiplied by the total number of bobbins. But it o unusual thing for a machine to develop an E.M.F. of several usand volts, and, were this method of joining-up adopted, ous difficulties in maintaining insulation would arise at the ends of the series where connection is made with the external uit, owing to the fact that there the potential difference between two adjacent coils would be the maximum developed by the hine. Consequently, the armature coils are always grouped in llel sets, generally two, as shown in fig. 139. By the arrange- t here illustrated, the potential difference between any two cent wires can never be more than that developed in one bin, but the total E.M.F. of the machine is reduced to half of t it would be, were the whole of the coils joined in series. 139 shows very clearly the way in which the coils are joined ther. Since the current is induced in the opposite direction in cent coils, it becomes necessary to connect alternately the two r and the two outer ends of the coils together, otherwise the F. of one coil would neutralise that of its neighbour. The ents generated alternate rapidly, but the arrow-heads indicate direction which the current takes at one particular moment. nd B_2 are the brushes connected to the external circuit, by ns of which the currents are conveyed from the insulated llic rings on the armature shaft.

There are at the Grosvenor Gallery Station two Ferranti mos, each of 625 horse-power, and a few details concerning

them will be instructive. The mean diameter of the armature i
7 feet, and it comprises 40 coils, joined up in two sets of 20. The
copper ribbon is 12·5 millimetres wide, and 0·75 millimetre i
thickness, twenty-five turns being wound over a core of bras
(insulated with asbestos) to form each coil, the convolutions bein
insulated by means of a continuous strip of fibre, 0·5 millimet
thick, wound on with the copper. The inner end of each coil i

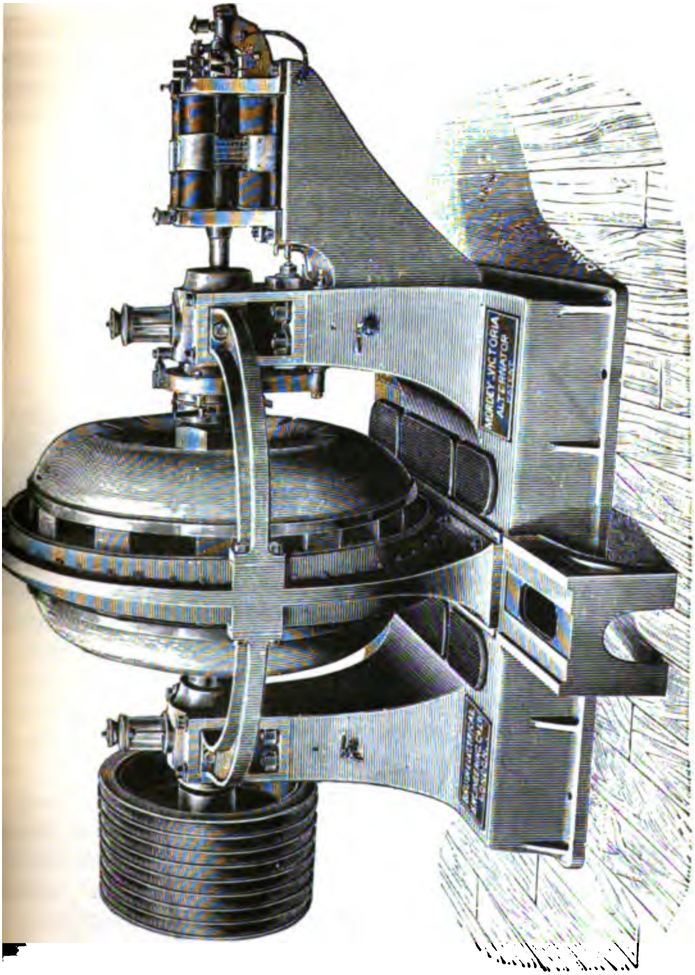
FIG. 139.



connected to the brass core, these cores being also electric
connected together in pairs, as indicated in fig. 139. In a so
what similar manner the outer ends of the coils are connect
together in pairs through the supporting framework.

The peripheral velocity of the armature is 6,050 feet p
minute, and, manifestly, special attention has to be paid to th
method of fixing the coils to prevent their flying out.

The external potential difference developed is 2,400 volts, b the adoption of the device shown in fig. 139 the maximum ential difference between the wires on neighbouring coils is re-

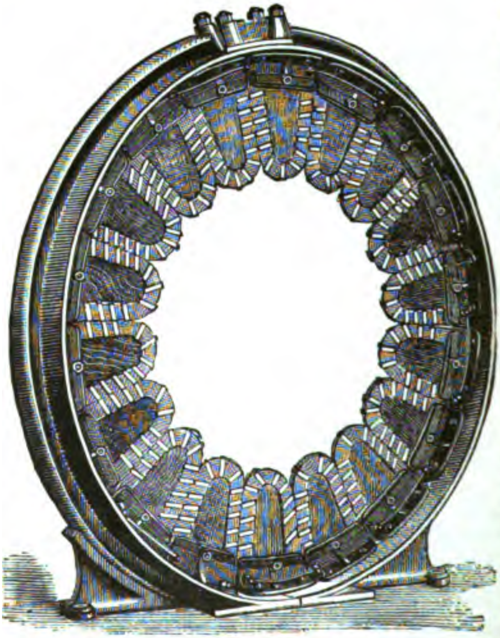


ed to 120 volts. The resistance of the armature from brush rush is 0·176 ohm.

The field-magnets are excited by a separate dynamo, twelve electrical horse-power being thus absorbed. There are 80 bobbins on each yoke-ring. The distance between the faces of opposite pole-pieces is only 0·875 inch, which is one of the important advantages pertaining to this form of armature; for the nearness of the opposite pole-faces reduces the wasteful leakage between adjacent pole-pieces.

One of the most interesting and most important machines of recent construction is that designed by Mr. W. M. Mordey, and illustrated in fig. 140. We have in this machine two departures from the practice adopted in constructing the machines previously described. In the first place, the armature is fixed, and the field-magnet rotated; and in the second place, the lines of force in the various fields projected through the armature coil are all in one direction, the pole-pieces on one side of the armature being all of north polarity, and those on the other side of south polarity. The waste of exciting power due to leakage between adjacent pole-pieces is therefore eliminated.

FIG. 141.

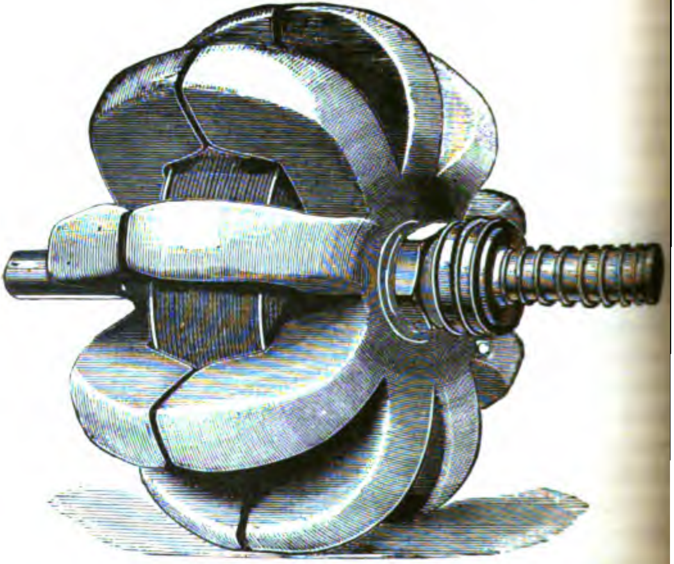


The armature, which is shown in fig. 141, consists of a number of coils of copper ribbon, wound on cores of paraffined wood or other non-conducting material, the different layers or turns of ibbon being insulated one from another, and the whole of the urns in each coil bound together with strips of prepared tape. Each coil is bolted at the outer or broad end between two brackets, he ends of the conductor being brought out through porcelain nsulators. The brackets, being bolted to the large gun-metal upporting ring, are securely and rigidly held in position, and the netal supports, which do not anywhere come between the poles f the field-magnets, are almost entirely beyond the magnetic ield. In this way the generation of wasteful eddy currents is reduced to a minimum, any slight loss that might arise from this cause being still further reduced by the employment of German silver for the brackets and bolts, as the high resistance of this alloy prevents the generation of any but exceedingly feeble currents. The gun-metal supporting ring, which is bolted to the bed-plate of the machine, is in two portions, being divided in a vertical diametrical line. These two parts, after having received the coils, are bolted together and to the bed-plate, the field-magnets being, however, previously placed in position. By this device single coils, should they become faulty, can be easily and quickly removed for renewal or repair; or each half of the armature can be removed without difficulty by sliding it on to the stool shown in the figure.

The shape of the field-magnet is most remarkable, and differs altogether from that of any other machine yet constructed.

It consists of a single electro-magnet built up in the following manner: A short cylinder of iron, through the axis of which the shaft passes, forms the core of the magnet, and is wound with the exciting coil. To each end of this cylinder or core is attached a massive iron casting of peculiar form, which will be best understood from fig. 142. Each casting consists of a number of horns or claws, which bend over from their common junction, so that the extremities of the two sets of pole-pieces approach within a very short distance of each other, the narrow polar gap or slit thus formed being only just wide enough to contain the armature coils without touching them when the entire field-magnet is revolved. The ends of the 'exciting' coil (which is to be seen inside the pole-pieces in fig. 142) are connected to collector-rings on the shaft, as shown at C to the right of the figure. These might be dispensed with, and the exciting coil, as well as the armature, might be made stationary. The core and its pole-pieces would then be the only portions revolving, and the electrical effect would be the same, but serious mechanical difficulties would arise in fixing the coil. Hence, it is far preferable to attach it to the rotating cylinder. The simplicity of this form of field-magnet is one of its great features, as a single exciting coil suffices for a machine of any size, speed, or number of alternations. The heavy rotating field-magnet acts very efficiently as a fly-wheel, and

FIG. 142.



ensures safety and steadiness of running, effectually neutralising, within certain limits, any pulsations due to irregularity in the stroke of the engine. Further, as the parts revolving at the highest velocity are simply solid masses of iron of the strongest description, the electrical and mechanical considerations which usually render low speed advisable do not apply here. The insulation of the armature coils is also simplified, and being stationary they need only to be supported with a view to resisting the drag of the ield. The armature is held in its vertical position by substantial orizontal brackets bolted on to the bearing-standards.

The method of joining the armature coils together is similar in rinciple to that illustrated in fig. 139, the inner ends of the coils eing joined together by short copper rods on one face of the rame, and the outer ends on the other face. The position of one of these sets of connecting wires or rods can be seen in fig. 141. The number of alternations during each revolution is the same as in the case of a Siemens or a Ferranti machine having an equal number of armature coils, although the number of pole-pieces is reduced to one half. This arises from the fact that the current in each coil is reversed at that moment when it is between two opposite pole-faces, and again when it is midway between two adjacent pairs of pole-pieces—that is to say, at the moment when it has the maximum number of lines of force thrust through it, and again when it embraces the minimum number.

Since the armature coils are similar as regards shape and the length of ribbon wound on them, and as the various fields projected through them are at any moment equal, the E.M.F. of any one coil an aliquot part of the whole; and, as all the coils are fixed, the E.M.F. developed in any one coil can be easily measured, and the gross E.M.F. deduced therefrom. As the range in a single coil is usually from 100 to 150 volts, an ordinary voltmeter, such as the Cardew, can be used for the purpose, whereas, to measure the total potential difference directly, an exceptionally high resistance voltmeter, or an electrometer, would be required. The machine is therefore fitted with a special pair of voltmeter terminals, connected to the ends of one coil, for the purpose of making this measurement.

Another point in favour of this machine is that the arrangement of the armature coils can, if required, be readily altered to vary the E.M.F. and current developed. For example, if it were required to reduce the E.M.F. of a 2,000-volt machine to 1,000 volts, this could quickly be done by dividing the armature coils into two sets and joining them together in parallel, the machine being then capable of developing twice the current strength. In any case the total electrical output, or the energy developed, would be the same.

The machine illustrated in fig. 140 is the latest pattern of the Mordey Alternator. In the earlier machines, copper dishes were attached outside the cast-iron claws of the field-magnets, for the purpose of reducing the amount of air-churning which would otherwise occasion loss of energy. The claws, in fig. 142, are shown without these dishes; in the newer form of the machine they are dispensed with, the claws being simply webbed together in the casting, when they present the appearance shown in fig. 140.

The field-magnet is excited by the current from a small Victoria direct-current dynamo, which is mounted on a bracket projecting from the main bed-plate, its shaft being coupled direct to the alternator shaft, so that the two machines are driven together.

A long thrust-bearing is employed to prevent end-play, since the space between the pole-faces and armature is very small, and it is adjustable longitudinally, for the purpose of enabling the field-magnet to be symmetrically disposed with regard to the armature. The armature terminals are placed on the upper portion of the gun-metal supporting ring.

The machine, when driven at 500 revolutions per minute, is capable of developing 75,000 watts, or 100 electrical horse-power, at an E.M.F. of 2,000 volts. 900 watts are required for the purpose of exciting the field-magnets. On account of there being no iron in the armature, and the attention devoted to small details such as the use of German silver for the coil-fittings, the waste of power due to eddy currents is very small; and this loss, added to that due to friction, which, owing to good mechanical construction, is also very low, amounts to but 5 horse-power, that being the power required to drive the machine at full speed on open circuit (or when the armature is disconnected), the field-magnets being excited to their maximum.

In many cases the output demanded from a dynamo varies considerably at different times. For instance, twice as much power may be required to supply lamps at one time as at another.

It is not economical to use one large machine, capable of meeting the maximum demand, and run it to give a small output at other times, but, fortunately, it is possible to join up two (or even more) alternating-current dynamos so as to feed the same ircuit simultaneously when required, switching out and stopping one when the other is able to meet the low demand.

The armatures must not be joined up in series, but in parallel, and the machines may be driven by belts from the same shafting, or, if necessary, from independent engines running at about equal speeds. In practice the latter course is usually adopted, since it is bad economy to employ a large engine to develop the power required by a small machine.

But parallel working is only practicable when in both machines the rates of alternation are equal, and the alternations 'co-phasal' —that is, when their maximum and likewise their minimum E.M.F.'s occur simultaneously. It is most remarkable that well-designed machines can correct each other and maintain this synchronism; but, as a most important part of the interaction depends upon the 'motor' properties of a dynamo, further consideration of the question must be deferred until electric motors have been dealt with.

CHAPTER IX.

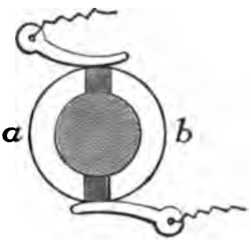
DYNAMO-ELECTRIC MACHINES (DIRECT CURRENT).

ALTHOUGH the sphere of usefulness for alternating-current dynamos has largely increased of late years, there is still a vast amount of work which such machines are, and always will be, wholly incompetent to perform. This is notably the case in connection with the deposition of metals by electricity, and in the 'charging' of secondary batteries. For these, and several other important purposes, it is essential that the current should be continuous, and flow in one direction only. It is possible to arrange matters so that all the currents generated by a dynamo shall be made to flow in one direction in the external circuit, the process being known as 'commutation,' and the part of the machine by which the alteration is effected is termed the 'commutator.' Directly this has been successfully performed, the dynamo is capable of a new and important development, for it is then possible to use all or a part of the current which is generated in the armature, for the purpose of magnetising the field-magnets. The smaller auxiliary machine, which, in most of the dynamos previously described, has been employed to excite the field-magnets, can therefore be dispensed with, and the machine made 'self-exciting.'

We come then to the consideration of the means to be employed in order that the currents which are generated in alternate directions can be commutated so as to flow in one direction *in the external circuit*. Referring again to fig. 120, we remember that the *direction* of the current is unaltered (although it varies in E.M.F., and therefore also in strength) during the first half-revolution of the rectangle, and that, at the end of that half-revolution, the reversal in direction takes place. Now, a moment's reflection will show that if, just at the end of this first half-revolution, the itions of the two brushes on their respective rings were internged, the current generated during the second half of the olution would flow in the same direction round the external uit as the preceding current did, because, although really gened in the reverse direction, it is entering the external circuit at other end. This is the fundamental principle of commutan; only, instead of shifting the brushes, the change is effected he right moment by a modification of the ring or rings against ch they press.

The simplest possible form of commutator is shown in section g. 143. Instead of two brass rings, a single brass ring or tube mployed, but with the difference that s split lengthways into two halves or ments, *a b*, insulated one from the er. Each end of the coil of wire is nected to one of these segments, and brushes or flat springs are so situated they press upon the divisions between segments at the moment that the coil n the vertical position—that is to say, he position where the reversal of the ent takes place. Just at that moment, then, the ends of the in contact with the respective brushes are also reversed, and result is that when the coil is rotated uniformly, a succession hort currents passes through the external circuit, each current g and falling similarly, but all impelled through the external uit in the same direction.

FIG. 143.

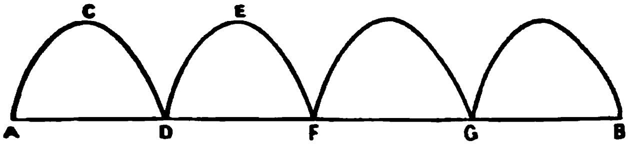


The length of the wire can easily be increased by winding it in mber of convolutions, instead of in a single rectangle, when, matter of course, the E.M.F. will be increased proportionately.

The variation in the E.M.F. developed by an ideal alternating-ent dynamo is shown in fig. 120, where the line A B represents normal or zero potential, the curves above it indicating the grarise and fall of, say, the positive potential, and those below it opposite, or negative potential.

Fig. 144 exhibits, in a simple manner, the result of replacing wo metal rings by a split tube, or simple two-part commutator. again indicates the zero potential, and the curve A C D the varying potential developed during the first half-revolution ; but, instead of the second half developing in the external circuit a negative potential, it is commutated into an external positive one, so that a series of currents, each of brief duration, is urged

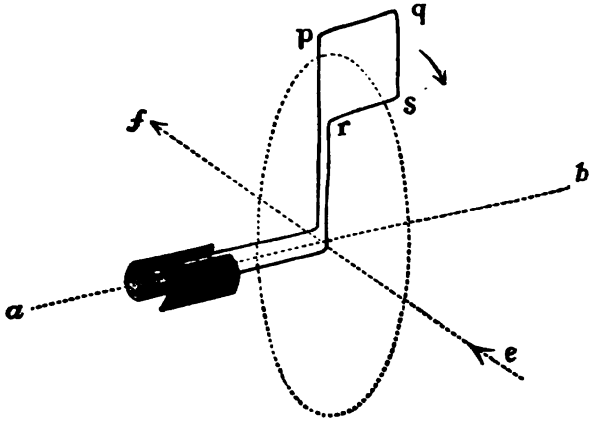
FIG. 144.



through the external circuit in one common direction. The total amount of current generated is, however, the same as before, although its strength oscillates rapidly between zero and the maximum.

A current varying so much in strength is, however, of almost as little service for many purposes as alternating currents, for, in most cases, the current must not only be uniform in direction,

FIG. 145.

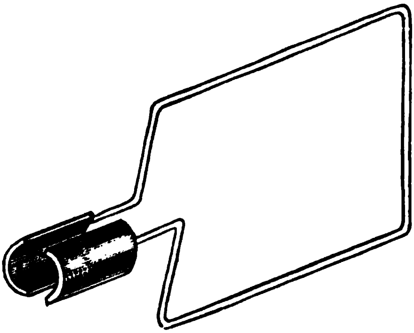


but constant in strength. The methods by which an *almost* steady current can be obtained will be understood more easily when studied in connection with an armature constructed of coils wound on a somewhat different system. In fig. 145, *a b* indicates axis of rotation, and $pqrs$ a single loop of wire which travels nd the circular path indicated by the dotted line. If we supse the lines of force of the field to be in the direction of ef, ng, or parallel to, a diameter of this circular path, then they will cut by the coil in a manner somewhat similar to that of the ctangular coil which we have just been considering.

The movement from the vertical position through the first half-volution produces a current which rises to a maximum when e coil has turned through an angle of 90°, and falls to zero again hen the coil reaches 180°, while the current generated in the ext half-revolution is exactly equal in strength, at corresponding ositions, though opposite in direction; but it can be commutated precisely the same way as in the case of the rectangular coil. The ends of the coil are connected to the metallic segments equivalent to a b in fig. 143) of a simple two-part commutator.

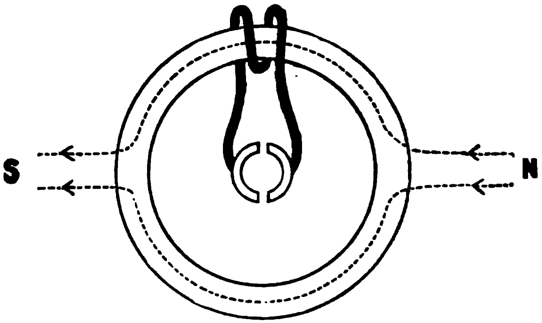
There is, however, one great difference between the two ethods. No portion of the coil shown in fig. 146 acts prejudicially, although the portions connecting the horizontal limbs are always idle, inasmuch as they do not cut, but only slide, through the lines of force. But with the coil shown in fig. 145 the case is different. There are still two idle connecting lengths, pr and qs, but the E.M.F. induced in the two horizontal limbs pq and rs is in the same direction in each—say from p to q and from r to s—because they always cut the lines in a similar sense, although at different rates; they therefore act in opposition to each other. But the outer limb pq traverses a greater portion of the field and moves at a greater linear velocity than does rs, and consequently, as it cuts more lines of force, and at a greater speed, than rs, the E.M.F. generated by it is the greater, the resulting current round the coil being therefore that due to the preponderance of the E.M.F.

FIG. 146.



of the limb *pq* over that of *rs*. Now, the lines of force which t outer limb cuts in excess of those cut by the inner limb are simpl those which pass through the coil when it is in the zero positio as in fig. 145, and it is evident that if the field is uniform and t coil comparatively small the lines thus embraced will be very fe indeed, and the use of iron to increase their number immediat

FIG. 147.

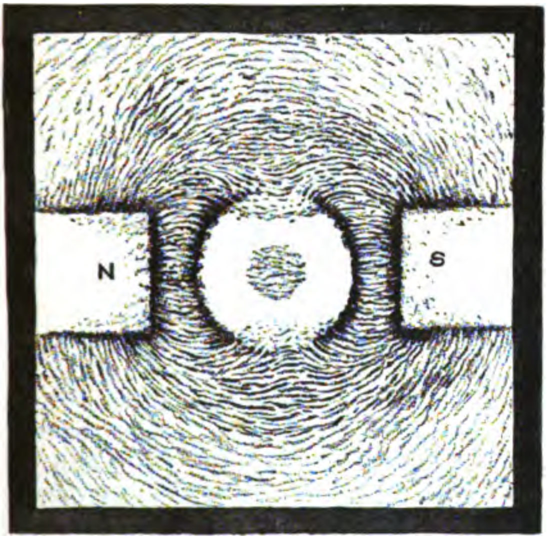


suggests itself. It is most advantageous to make the iron in t form of a ring, as shown in fig. 147, and cause it to rotate with t coil.

In fig. 148 is illustrated the effect of placing a ring of iron i magnetic field. The apparatus employed to obtain this fig consisted of a quantity of thin soft iron wire wound into a r and placed between the opposite poles of two powerful bar magn a sheet of paper being laid over them, and iron filings sprinkl upon it. The spaces free from filings represent those places wh the permeability of the iron is sufficiently high to prevent appreciable number of lines of force extending above the p so as to give direction to the filings. The manner in which lines converge into the ring should be noted, and it will also observed that at two places, on a diameter at right angles with lines, the magnetic effect above the paper is considerable. reason for this is that the greatest number of lines pass thro the iron at these points, and the permeability is sufficiently red to allow some lines to leak above the paper. Comparatively lines pass diametrically across the ring, about half of them g hrough the upper and half through the lower part of it, and herefore the inner limb of the coil (fig. 147) cuts but very few ines, and the resulting E.M.F. is practically that developed by the outer limb alone.

In the case illustrated in fig. 147 only one-half of the total number of lines of force urged through the iron can, at any one time, pass through the coil, and some device is therefore necessary to enable the other half to be utilised. Now, since the induced E.M.F. is the same in any given position after the coil has passed 180° as it was in the corresponding position after it had passed the zero point, it is clear that a second coil might with advantage be placed at the opposite extremity of a diameter of the circular path described by the coil. We will assume that the limbs on the outer periphery alone are active, and it will be seen that if the induced current flows from front to back in the outer limb of the upper coil, it will flow from back to front in the outer limb of the lower coil, because these limbs always cut the lines from opposite

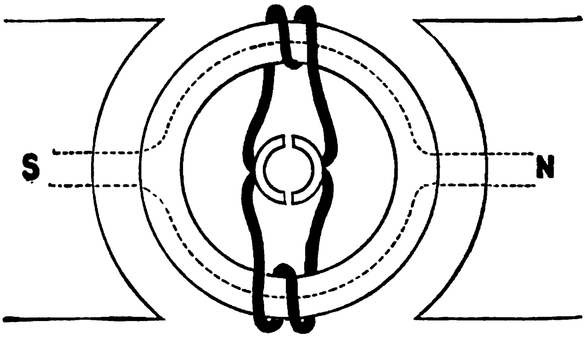
FIG. 148.



sides, viz. one from above and the other from below. The E.M.F. is, however, at any moment equal in each, and, by joining the ends which are at a positive potential to one segment and the ends which are at a negative potential to the other segment, both coils are made to deliver their currents in the same direction to the external circuit.

Fig. 149 illustrates the arrangement for employing two such coils; they are similarly wound (right-handedly in this case), and

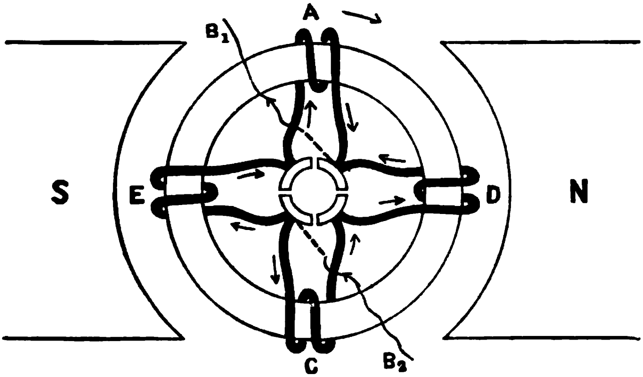
Fig 149.



their *adjacent* ends are joined to the same section of the commutator. Now, as they are at opposite extremities of a diameter, they pass at every moment through parts of the field where they act with equal effect, and therefore, as already pointed out, the E.M.F. will be the same at the extremities of each coil. Since the ends of the two coils, which are at the same E.M.F., are joined to the same segment of the commutator, the E.M.F. due to both coils is only the same as that produced by one of them. It is, in fact, an exactly analogous case to that of joining two primary cells of equal E.M.F., in parallel. There is also the similar advantage here that because the coils are joined in parallel the internal resistance between the two segments is only half that of one coil, and, as we have seen, any arrangement that so reduces the internal resistance of a current generator is sometimes very valuable. By increasing the number of turns in the coils we increase the E.M.F., because a greater number of conductors in series, round the perhery, are usefully cutting lines of force; but, of course, the umber must be exactly the same in each coil. In figs. 147 and 49 there are two active conductors to each coil.

We are now in a position to proceed with the consideration of method for making the short fluctuating currents depicted in g. 144 approach more nearly to a continuous steady current. hese short currents are at a minimum when the coils are at right ngles to the lines of force, or at that point where the reversal of e induced current takes place, and it is evident that if a second air of coils be placed at right angles to this existing pair, as in g. 150, they will always lie parallel to the lines of force, or be in

FIG. 150.

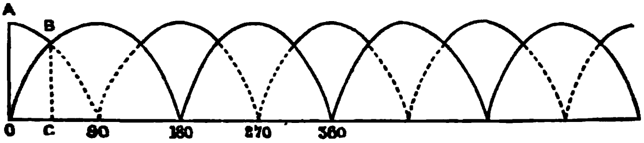


e position of best action, just at the moment when the first pair e almost idle. But it now becomes necessary to divide the mmutator into four parts, all the coils being, of course, similarly ound, and the adjacent ends of adjacent pairs connected to the me segment of the commutator. When only two segments are nployed, the brushes, as we have observed, are placed so that e divisions of the commutator pass them just at the moment hen the coils are at right angles to the lines of force, and when ey are almost idle. In the present case, with four coils, the ushes must also be placed so that the division between each ir of segments on the commutator passes a brush when the coil nnected to that pair of segments is in the position of least activity, viz. with its plane at right angles to the lines of force. We shall see presently that there are several causes which combine to slightly vary this particular position, although it can always be found.

In fig. 150 the brushes are indicated by dotted lines, and are shown slightly out of what we have hitherto considered to be their correct position. Supposing the lines of force to pass straight across from one pole-piece to the other, the currents in the various coils would be in the direction indicated by the arrows, and the resulting current could be led from the armature to the external circuit by the upper brush B_1, entering the armature again by the lower brush B_2. The two horizontal coils D and E are in the position of greatest activity, while the vertical coils A and C are almost idle, and merely serve to conduct the current generated by the active coils to that segment of the commutator which the brush is touching. A moment later A and C will each begin to generate a current in the opposite direction to the one now flowing in them, but as by that time they will have passed the brushes, their opposite ends will be in contact with the same brushes, and the direction of the current in the external circuit will remain unaltered. When the plane of each coil makes an angle of 45° with the lines of force, they are equally active, and the E.M.F. at the brushes is twice that which is at that moment being developed by one coil.

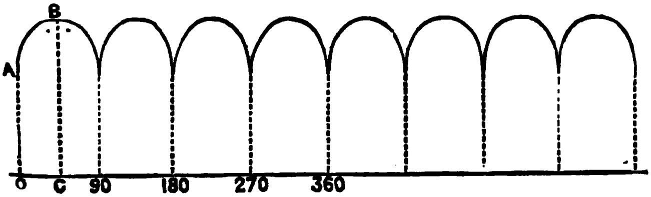
The resulting E.M.F., due to the joint effect of the double instead of the single pair of coils, is still far from constant, and, as before, we must determine at what positions of the coils the E.M.F. is at a maximum and where it becomes a minimum. The curve (fig. 144) illustrates the variation of the E.M.F. due to one coil or one pair of coils, and as, when this E.M.F. is highest, that of the second pair of coils is lowest, and *vice versâ*, the relative magnitude of the E.M.F. generated by two pairs of coils at different positions may be indicated by the overlapping curves in fig. 151. From this we wish to construct a curve which shall show how the E.M.F. *at the brushes* due to the effect of both pairs of coils varies. Now, twice during each revolution one of the two pairs is for the moment acting alone, and, consequently, the E.M.F. at the brushes is simply that due to this pair, and is proportional to the length of the perpendicular line O A. At this moment the E.M.F. at the brushes is at its lowest value, and the length of this line O A determines the lowest point on the curve which we desire to construct. Immediately after this point is passed both pairs are acting together, the activity of one increasing and that of the other

FIG. 151.



decreasing. At a certain stage they will be acting with exactly equal effect, and this stage is indicated by the intersection in B of the two curves; it occurs when each coil makes an angle of 45° with the lines of force. To obtain, therefore, the resulting E.M.F. at the brushes, we must add together these two equal E.M.F.'s; consequently, twice the length of the line C B must be taken as the height of this the highest point in the new curve. When the coils have rotated through another 45°, one pair is again idle and the other at its maximum activity, so that we again reach the lowest point of the curve. The curve so constructed is shown in fig. 152, and indicates the manner in which the total

FIG. 152.

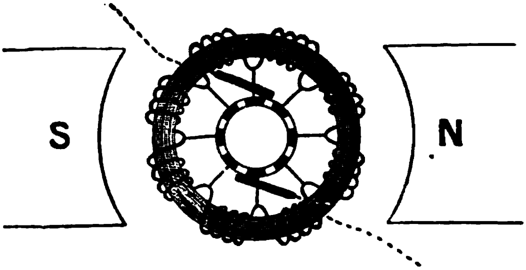


E.M.F. at the commutator brushes fluctuates when the armature consists of two pairs of coils arranged as in fig. 150. The resulting current will also fluctuate similarly, depending in strength upon the gross resistance in the circuit.

A little reflection will make it obvious that the variation in the E.M.F. can be further diminished by the employment of a yet greater number of pairs of coils in the armature, providing that they are placed so that they each come into the position of best action at the moment when the resulting E.M.F., without their individual aid, would be at a minimum.

For instance, a coil might be placed exactly midway between each of those wound on the armature shown in fig. 150; the armature would then consist of eight coils in four pairs, and the commutator of eight bars or segments (fig. 153). The current from such an armature would be far more steady than one from the four-coil armature; in fact, it may be stated generally that the greater the number of coils composing the armature, the less the fluctuation of the current. Of course there is a practical limit to the number of coils; for instance, the commutator with this kind of armature must have as many segments as the armature has single coils, and its construction and the making of the necessary connections would be difficult and expensive if the number were excessively increased.

FIG. 153.



It will be observed that in fig. 153 the whole armature conductor is wound continuously round the core; it is divided into sections having four convolutions each, and a connecting wire is led from the junction of every two adjacent sections to the proper segment of the commutator. The result is of course the same as if the ends of each section were brought direct to the commutator segment, while the actual length of the armature conductor, and therefore the resistance, is slightly reduced. The black portions of the circle represent the metallic segments, the white spaces between them indicating the insulating material.

In order to increase the E.M.F. developed in a given field at a en speed, we must increase the number of conductors on the er periphery of the armature, which can be done by adding to number of convolutions, although this also increases the in-al resistance. In the armature illustrated there are thirty-two ve portions of the wire round the whole external periphery, but hey are joined up in two sets in parallel, the total E.M.F. is y sixteen times that of one active portion.

If we know the number of active conductors joined in series the number of lines of force which they cut per second, it is y to calculate the resulting E.M.F. The E.M.F. developed by particular conductor moving circularly in a uniform field varies i its position, and is, as we have seen (Chapter VIII.), pro-tional to the cosine of the angle which the plane of the coil of ch it forms a part makes with the lines of force; or to the sine he angle through which the coil has turned from its position ight angles to the lines of force. But we need not now trouble selves with this consideration, for, in a symmetrically con-cted armature of many convolutions, the place of each con-tor as it moves to a position of greater or less activity is nediately filled by another, and the total E.M.F. remains un-red. Since each active length undergoes precisely the same active effects, the average E.M.F. induced in each is the same, the total E.M.F. will be equal to the number of active con-tors round one-half of the armature multiplied by the average .F. developed by one of them during half a revolution.

Supposing the armature to consist of forty-eight convolutions the E.M.F. developed by one of the active limbs to be 2 volts, n the whole E.M.F. would be $2 \times 24 = 48$ volts.

The average E.M.F. developed by each active conductor de-ds upon the speed at which it moves, and the number of lines by it; in fact, we have seen that if a wire, one centimetre long, moved at a velocity of one centimetre per second transversely ough a field of unit strength (that is, a field having one line of e per square centimetre), then the resulting E.M.F. will be al to one C.G.S. unit. This unit being so very small, the volt aken for practical use, having a value 10^8 or 100,000,000 times t of the C.G.S. unit. So that after calculating E.M.F. in C.G.S. its, the result must be divided by 10^8 to obtain the E.M.F. in volts.

It is preferable to know the number of lines cut per second, and then we need not know the length of the conductor or th strength of the field in C.G.S. units, nor need the field be unifor Referring again to fig. 153, suppose there are 16,000 lines of fo forced through the armature core, these lines will all be cut twi by each conductor during one complete revolution. If th armature makes one revolution per second, each conductor w cut 32,000 lines per second and generate an average electro-moti force of 32,000 C.G.S. units. And as there are sixteen conduc in series, the total average E.M.F. as measured at the brushes w be 16 × 32,000 = 512,000 C.G.S. units, or

$$\frac{512{,}000}{10^8} = \cdot005 \text{ volt nearly.}$$

If the armature made ten revolutions per second, the E.M.F. wou be ten times greater (i.e. 0·05 volt), because each conduc would now cut ten times the number of lines per second.

In fact we may say that the average E.M.F. generated in t armature of this description is equal to

$$N \times \frac{P}{2} \times 2n, \text{ that is, } NPn \text{ C.G.S. units,}$$

or

$$\text{average } E = \frac{NPn}{10^8} \text{ volts,}$$

where N is the total number of lines of force urged through t armature core; P the total number of active conductors ly round the periphery, and $\frac{P}{2}$, therefore, the number in series; the number of revolutions per second, and $2n$, therefore, t number of times per second which the whole of the lines are c by each conductor.

The E.M.F. obtained in the last example (0·05 volt) is ve low, because we assumed a rather low speed and few lines of for In practice it is not unusual to force several millions of lin through the armature core. Supposing the number to be 3,000,00 and the number of conductors round the periphery to be 150, th if the armature is driven at 1,200 revolutions per minute, or 20 p second, the E.M.F. developed would be

$$\frac{3{,}000{,}000 \times 150 \times 20}{100{,}000{,}000} = 90 \text{ volts.}$$

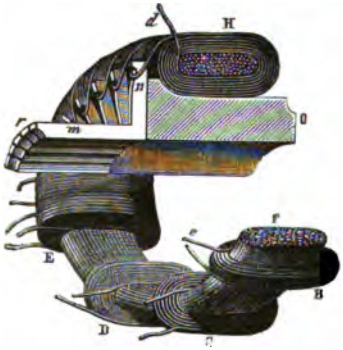
The above is a fair example of what obtains in actual practice, the student will readily perceive that it is necessary for the ntity of iron in the armature core to be considerable, otherwise such a large number of lines of force the magnetic induction ugh it (that is, the number of lines per square centimetre) ld be abnormally high. We know that the permeability of decreases rapidly when the induction through it exceeds a in amount, and then a large number of the lines leak diaically across the ring instead of taking the path indicated in 149, many of them passing across the steel driving shaft, the eability of which may be nearly equal to that of the 'satul' iron.

Now, as these lines of force thus leaking across the ring are y the inner portions of the conductor (equivalent to *r s* in 45) and act prejudicially, inasmuch as the E.M.F. generated by nner wires in cutting them is reverse to the main E.M.F., it is ntly inadvisable to endeavour to push the induction too far. rule the limit is from 16,000 to 18,000 lines per square centie, and if more lines through the core are needed, either the must be increased or iron of higher permeability employed. former necessarily entails a greater length of conductor. It dent that in an armature of the type we are considering, the of which the core is made should be of the highest possible eability, while the quantity of iron or steel used inside the should be as small as possible to minimise the tendency to -leakage. This latter consideration implies that iron should e employed for the purpose of mechanically connecting the to the shaft. In practice, gun-metal or some other nonetic alloy is used.

he first armature on this principle was constructed by otti, but it remained unnoticed until the essential features een combined in a slightly different form by Gramme.

ig. 154 illustrates the construction of an early form of Gramme ture, the core being shown cut through, and some of the coils ced to make it clearer. The core, F, consists of a quantity n wire wound continuously to form a ring of the shape shown e section. Over this is wound about thirty coils of insulated r wire, B C D, &c., the direction of the winding of each being the same, and their adjacent ends connected together. commutator segments consist of a corresponding number of angle-pieces, *m n*, which are fixed against the wooden boss, carried on the driving shaft.

FIG. 154.



The junction of every two adjacent coils is connected to the commutator segments, as shown, and two flat brushes of wire are pressed against the jecting ends of the segments, serve to deliver the current the external circuit. The forms of this armature, identical in principle, are superior from a mechanical of view; in fact, the here illustrated would fly to if subjected to the stresses occur in a modern machine.

It is necessary that the mutator bars should be firmly in position, that the wire should be bound or by some fixed so as to prevent its being shifted, and that the core with it the coils should be firmly secured to the driving shaft. far as possible it will be shown, in describing the best machines, how well these points are attended to in Especial care must be taken to prevent the generation of currents in the core, and this was the reason why Gramme rather fine wire instead of a solid ring. We have previously marked that the E.M.F. which gives rise to these eddy very low (although the current strength may be because a large mass of metal offers little resistance), and therefore, the merest film of insulation between wires of the core is sufficient. Except in special cases a shellac varnish, or even a coating of rust, is all that is and it should be borne in mind that the space occupied by lation should always be as small as possible, so as to maximum amount of iron to be used. If the armature is in a simple field between two pole pieces, it is not subdivide the core to the extent adopted in the earlier

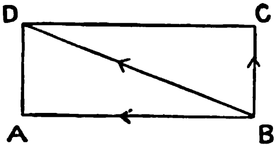
:hines, for since the direction of the eddy currents is at right les to the lines of force and to the direction in which the core res, there will be no tendency for them to flow in a radial ction, but only along lines parallel to the driving shaft. refore the core may be simply laminated, or built up of a iber of thin discs of soft iron, thus giving better facilities for hanical connection with the shaft, and also reducing the netic resistance considerably. In entering or leaving the rior of the wire core, the lines of force have to leap across ierous little spaces of low permeability, while in the case of a built up of discs, not only is the mass of iron greater, but it so continuous in the direction of the lines, and discontinuous in the path which would be taken by the eddy currents.

Returning now to a consideration of the phenomena developed he actual rotation of the armature, we may repeat that the hes must be so placed that every division between the segts of the commutator passes a brush just at that moment n the coil, the ends of which are connected to those segments, le. Now this happens when the plane of the coil is at right es to the lines of force, so that if the lines of force always ned their regular straight direction between the poles of the magnet, it would be easy to fix the correct position for the hes. But, unfortunately, the field is considerably distorted ediately the armature is caused to rotate and the current blished. This distortion is due to the fact that the armature f becomes a powerful electro-magnet, having lines of force h are not coincident with those of the field magnets.

The two halves of the core are, as a matter of fact, magnetised he currents passing round them, and in such a manner that similar poles are adjacent to each other and situated at the ts where the two currents enter and leave the external circuit. r, if two semicircular magnets of equal strength are placed so form a circle with their *unlike* poles adjacent, they form a plete closed magnetic circuit, nearly all the lines of force ig the path of the iron or steel, and there is consequently very external magnetic effect observable. But if these same semiilar magnets are placed with their *like* poles adjacent, there is ndant external evidence of the magnetic strength of the combination. The circle acts, indeed, as if it were a single magnet, the distance between its poles being the length of the diameter. Some of the lines of force find their way back across the diameter to the opposite pole, while others pass round outside the circle, a much larger proportion taking this course when, as in the case of the dynamo, there are large masses of iron in the vicinity. The position of the brushes determines the position of the poles of the armature, and when the brushes are placed on a diameter at right angles to the lines of force of the field, these poles are also at right angles to those lines of force.

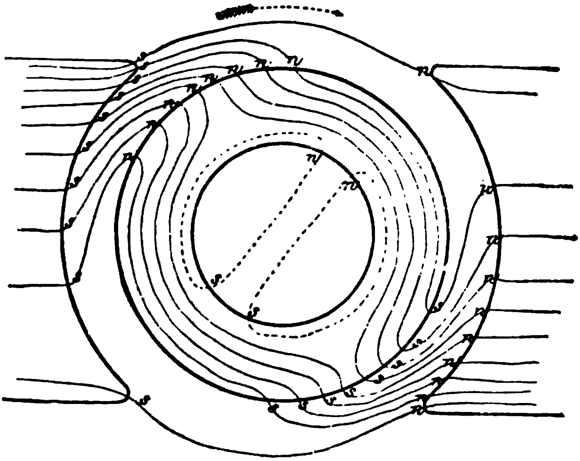
It is manifest that as the tendency is for the armature to generate a magnetic field in one direction, while the field magnets strive to maintain one in another, the direction of the resultant field must lie between the two, the exact position depending to a great extent upon the relative magnetising forces of the armature and field magnets. Were these relative forces known, the direction of the field might be determined approximately by the well-known 'parallelogram of forces' (see fig. 155). In this case the line A B represents by its position the direction, and by its length the magnitude of the magnetising force due to the field magnets alone, while the line B C, drawn at right angles to A B, represents the direction and force of the field due to the armature. Then the diagonal B D of the completed parallelogram represents both the magnitude and direction the resulting magnetic field. Now the brushes must be set on a diameter at right angles to these resulting lines of force. Hence this shifting of the field due to the reaction of the armature necessitates also the shifting of the brushes through a corresponding angle, equal, in fact, to the angle D B A.

FIG. 155.



This altered position of the brushes is commonly known as the *lead* given to them, and the angle through which they are moved is known as the angle of lead. In every dynamo the lead is forward, or in the direction of the rotation of the armature. But the parallelogram of forces referred to above does not exactly indicate the true angle, because immediately a lead is given to the hes, the polarity of the armature is shifted through a corre- ding angle, the result being to still further distort the field again increase the angle of lead. It will be evident that e wish to reduce the angle D B A (fig. 155) it can be by decreasing B C or increasing A B, which in either case d result from making the magnetising force of the field ets great as compared with that of the armature. Practice dictates, for this and for other reasons, that the magnetic in which the armature revolves should be as strong as ble, and always very much stronger than that developed by rmature itself. In fig. 156 is illustrated the direction of the

FIG. 156.



tant field of a dynamo when the armature is revolving in the tion indicated by the arrow, and is generating a current. It be observed that the lines of force *n s*, *n s* are considerably rted or dragged out of their normal position, and that this rtion takes place in the direction of rotation. The lines h cross the space inside the armature ring indicate the direc- of leakage, corresponding to that illustrated in fig. 148.

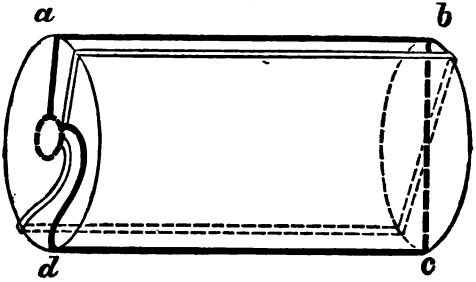
When the external resistance through which a dynamo is ting is varied, the current in the armature, and therefore the field produced by it, also varies ; the same cause may also al the field produced by the field magnets if the machine is 's exciting,' and consequently in practice the angle of lead sometim varies considerably. If the effective fields produced by the fi magnets and the armature were varied in the same proportion, angle of lead would remain constant ; but we shall see pres that because the induction through and the permeability of field-magnet and armature cores do not vary together, as wel for other reasons, this proportion is not maintained, although currents producing those fields may be equally increased diminished. Too much stress cannot be laid upon the nece for setting the brushes in the proper position, and to facil matters they are usually mounted on an insulating rocker so they may be shifted together through a considerable angle the correct position is found. When the field is a simple such as that between the two poles of a magnet, and provi is also uniform, the brushes are placed at opposite extremi a diameter of the commutator.

When the brushes are not properly adjusted, the coil short-circuited while they are more or less active, and consid sparking occurs at the commutator, injuring that importan of the machine, and giving evidence of wasted energy.

Practically the best position of the brushes can be fou shifting them while the machine is running (the external c being at the time completed) until there is very little or no ing observable ; and it is found that they must be set even a further ahead than the point where they are at right angles t direction of the resultant lines of force. This slight extra l necessitated by the rather peculiar and important action takes place in a coil as it passes a brush. The brush l sufficiently wide bearing on the commutator to bridge ov interval between the two segments and so to short-circuit th attached to them for a brief interval of time ; and althoug may take place when the coil is in itself, as a generating almost inactive, it must be remembered that it has consid self-induction, consisting as it does of a number of convol of wire wrapped round a comparatively large mass of soft We have considered at length the reasons which prev [illegible] being suddenly started or stopped in any circuit which [illegible] an appreciable amount of self-induction, from [illegible] that although the coil itself may not be [illegible] it is carrying the whole of the current [illegible] coils in the same half of the ring [illegible] the current will not [illegible] for a [illegible] tures, commonly known as 'drum' armatures, are construc upon the principle of the rectangular coil first mentioned. Th earliest drum armature was devised by Von Hefner Alteneck, was really a natural development of the shuttle armature so used in small magneto machines. This shuttle armature, consi ing, as it does, of one coil of many turns, gives a current fluctu from maximum to zero twice in each revolution, and gre steadiness was aimed at and obtained by placing a number of c symmetrically round the core; in just the same way that a consi able number of coils wound on the Gramme principle yields a m nearly constant current than would result from a single coil. drum armature is somewhat more difficult to construct and illustrate, and although the fundamental principle is in all c that just indicated, there are many ways of making the nece connections, some of which will be described when dealing actual machines.

The general principle may be gathered from fig. 157; only two adjacent sections are shown, each having one turn. T core is shaped like a cylinder, or drum; a commutator, s to those already scribed, being p at one end in a with its axis. F one segment the coil ascends up face of the drum *a*, thence length along the cylin to *b*, whence passes across a

FIG. 157.



meter to *c*, and along the length of the cylinder to *d*. Fr it is brought round the face and connected to the segment to that one to which the other end of the coil is joined. T second coil, shown by open lines for distinction, starts i the segment at which the first coil terminates, and is wo similarly to that coil, being placed a little further round drum as shown. Its two ends are connected to adjacent s ments, and, in a similar manner, coils would be placed all ro ie cylinder, equidistant, and with the ends of each joined to two djacent commutator segments, so that each segment has two wires onnected to it. Many of the best drum armatures are constructed ith but one convolution in each section, but when it is desired o increase this number the wire is simply wound the requisite umber of times round the cylinder, and the end of the last convolution led from the point *d* to the commutator segment. Of ourse, the wires cannot be brought diametrically across the faces, s shown at *b c*, on account of the driving-shaft, and when there re several convolutions in each section care is taken to place an qual number of the wires on either side of the shaft, so as to reserve a mechanical as well as an electrical balance. In any ase, great care has to be taken with these cross-connections, which are, in fact, a serious source of trouble, for, since portions of all the coils overlap here, it is possible to get wires having a high potential difference very close together. This difficulty does not arise with a Gramme ring.

The great advantage peculiar to a drum armature is the fact that the conductors usefully cut *all* the lines of force passing through the armature core. The only idle wire is that used for connection across the faces or ends of the cylinder; and no part of the conductor can generate an E.M.F. in the counter direction. Consequently, iron may be employed for all the internal fittings; in fact, but for the necessity for allowing space for ventilation, the whole of the inside of the armature might be occupied by iron. Since the active limbs, *a b*, *c d*, always cut the lines of the field from opposite sides—viz. one from above, the other from below—the current is induced, from front to back in one and from back to front in the other, so that it circulates in the same direction round the coil.

Each coil is equivalent, then, to two diametrically opposite coils in a Gramme armature, and there will be the same number of commutator segments as there are coils. The reversal of the current, of course, takes place as each coil passes the zero position —viz. with its plane at right angles to the lines of force—and it is in this position that the segments to which it is connected pass the brush. Also, as in the case of the Gramme ring, the resistance from brush to brush, through two halves of the armature in parallel, is only one quarter of that of the whole armature in series, and in calculating E.M.F., the formula, $E = \frac{N P n}{10^8}$, holds good, P bei the number of active conductors, such as *a h*, round the periphe of the drum.

The drum armature is far more efficient than any other fo and we may briefly compare the relative advantages of the dr and ring type by supposing that we have two armatures of eq diameter, and having conductors arranged round them equal number and length. The magnetic resistance offered by the d armature will be the smaller, because the quantity of iron in core is greater, and therefore a given 'magneto-motive force' urge more lines of force through it than through the armature.

Further, the whole of the lines passing through the d armature are usefully cut by the conductors, while, in the ca the ring, some leak across to the shaft and are cut by the i portions of the wire in such a manner as to reduce the main l Therefore, with a given magneto-motive force to maintain field, the drum armature will give a much higher E.M.F. tha ring when they are driven at equal speeds. Equal E.M.F.'s m be obtained by reducing N, the number of lines of force, or P. number of active conductors; but the factor which it is us sought to keep as low as possible is *n*, the number of revolu per second. One great practical advantage of a drum arma that it enables slow-speed machines of comparatively mode proportions to be constructed, and it will be observed that slow-speed dynamos have ring armatures; indeed, the drum p having recently lapsed, very few simple ring armatures are now in any but small machines. Since the proportion of idle wi slightly less in the drum than in the ring type, its cond resistance is rather lower, while, on the other hand, it has the advantages that it is difficult to make it as strong mechanical the ring, the cross-connections are somewhat troublesome, an a rule, special arrangements are needed to ensure sufficient lation.

Having discussed some of the theoretical points involved the construction and action of direct-current dynamo arma will now consider the methods of maintaining the field, which, ill be remembered, must be as strong as possible. As in the of the more powerful of the machines described in the preng chapter, electro-magnets (called the field-magnets) are loyed for this purpose, and great care should be exercised in design. Practical difficulties and economy in construction ewhat influence the shape, but in every case the great object ld be borne in mind, viz. the necessity for leading as many of force as possible through the space between the poles, in h the armature is made to revolve.

The actual magnetising force, consisting of a current passing igh a coil of wire, is proportional to the amperes of current ng and the number of turns of wire in the coil, and, as has dy been fully explained (Chapter VII.), the quantity repred by the product of these two factors is referred to as the ere-turns.'

Iow, for any given machine, the number of lines of force h must be urged through the armature is usually determined ehand, but as with every electro-magnet, of whatever design, is a certain amount of 'leakage,' only a portion of the lines rated by the ampere-turns pass through the armature.

ut power is expended in the generation and maintenance of ines of force, and those which are rendered useless by leakage sent so much power wasted. It is obviously imperative that waste should be reduced to a minimum, and the greatest posproportion of the lines developed led through the armature. may be accomplished by making the magnetic resistance of path very low. The whole magnetic circuit should, preferapproximate to the circular form, and whether good soft iron st-iron is employed, its sectional area must be sufficient to nt the saturation point being readily reached.

he spaces between the pole-pieces of the field-magnet and ore of the armature offer considerable magnetic resistance, h may roughly be taken as nearly proportional to the distance een the iron surfaces, the permeability of the copper wire and sulation being about the same as that of air. The only way vercoming this serious difficulty is to reduce the distance een the iron surfaces as much as safety will permit, and, since this minimum distance is nearly the same in machines of all sizes, we see one reason to account for the observed fact that small dynamos are less efficient than larger ones.

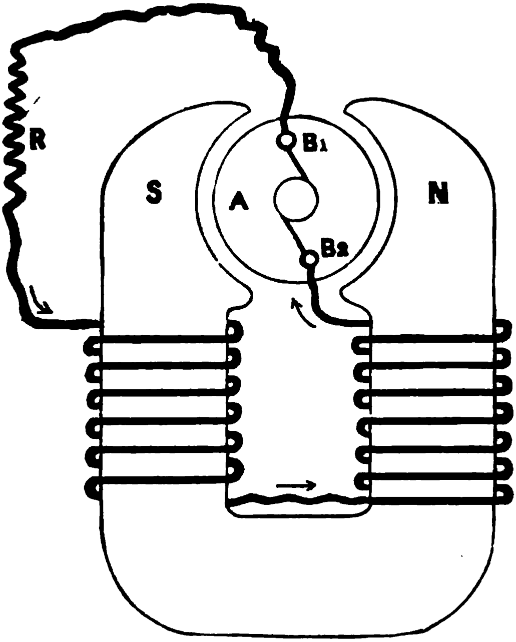
It must not be forgotten that while the permeability of iron decreases with an increase of the magnetic induction through it, that of air remains constant, and the difference between the permeability of the nearly-saturated iron of the field-magnets, and that of the air space, is never anything like the difference usually given for unsaturated soft iron and air.

Two very important considerations influencing the constructi of field-magnets are economy and mechanical strength, and i practice, as we shall see, it is often considered advisable where th weight is unimportant to use cast-iron for part or all of the fiel magnet core. It is preferable to forge or cast the core in o piece, as joints break the molecular continuity and increase th magnetic resistance considerably; this disadvantage is minimi by making the surfaces in contact fit truly. The principal pra tical objection to the use of cast-iron is that, since its secti area must be at least twice that of wrought-iron, a much gre amount of copper is required to form the field-magnet co Copper, even now, is expensive, while cast-iron cores are far le costly than equivalent ones of wrought-iron, and the stud should observe how different makers aim at true economy in th matter. Even leaving out the question of cost and weight, it do not by any means follow (as is sometimes supposed) that a dyn properly designed to perform certain work, and having cast-iron i its construction, is inferior to one built wholly of wrought-iron t perform the same work.

The composition of the 'ampere-turns'—that is, the prop tion of current strength to the number of convolutions— depend largely upon the manner in which the exciting current obtained; for it is sometimes necessary to have considera resistance in the coils, and then the number of convolutions m be made great and the current correspondingly weak; while i other cases a high resistance is inadmissible, when only a few t can be employed, and the necessary magneto-motive force m then be obtained by the aid of a heavy current.

At the beginning of this chapter we referred to a very imp benefit following the commutation of the current, viz. the sibility of using all or part of the current generated in the ature for the purpose of magnetising the field-magnets, and simplest method of doing this, in which the whole of the ent is so employed, is exemplified in fig. 158. A machine

FIG. 158.



ng its connections made in the manner there shown is known 'Series Dynamo.'

N are the pole-pieces of a massive horse-shoe electro-net ; the armature A revolves in the space between them, B_1 B_2 g the brushes which press against the commutator, and by ns of which the current generated in the armature can be led ny desired point. In this case, one end of the wire forming coil of the electro-magnet is connected directly to the brush he other end being joined through the external circuit R to the opposite brush B_1, so that the circuit of the field-magnet is completed through the armature coils. Hence the whole of the current generated in the armature must pass round the coils and magnetise the electro-magnet. But how is the current to be started in the first instance? It so happens that even the purest soft iron is found to retain some of the magnetism imparted to it, therefore the cores of a dynamo always retain an appreciable amount.

This 'residual' magnetism is sufficient to project a few lines of force through the armature coils; so that, when the armature is rotated, a feeble current is generated in them. The connections being made as in fig. 158, this current leaves the armature by the top brush B_1, flows through the external circuit, and, returning to the machine, passes round the coils of the field-magnets, the circuit being completed through the lower brush B_2. The feeble current sent in this way through the field-magnets increases the strength of the field in which the armature rotates, and, consequently, the current generated also becomes stronger. This further increases the magnetic field developed, and, consequently, also the current strength, action and reaction succeeding one another, until presently the current becomes very strong indeed. This increase does not, however, continue indefinitely, there being two especially important restrictions which tend to fix a limit to the current produced. In the first place, although the core of the field-magnet may be very massive, its magnetisation eventually approaches the saturation-point, beyond which an increase of the current in the coils would not by any means involve a corresponding increase in the strength of the effective field. Secondly, the rotation of the armature, although performed with little effort at the commencement, requires a considerable expenditure of energy as the strength of the current increases. We are even able to estimate the relative amounts of the power required to turn the armature while currents of different strengths are being generated. For the present purpose the calculation can be made very simple by ignoring the power lost in mechanical friction, &c. The electric power which is being developed in any circuit can be found by simply multiplying together the electro-motive force in volts and the current strength in amperes in that circuit, the result being he number of watts of power developed therein, or $W = EC$, W eing the number of watts.

As the E.M.F. is equal to the product of current strength and resistance (that is, $E = CR$), we may write $W = CR \times C = C^2R$—that is, the power in watts developed is equal to the resistance in ohms multiplied by the square of the current strength in amperes.

As the resistance of the dynamo armature and magnet coils is always known, only one measurement, that of current strength, need be taken, which can be done by any ammeter of negligibly low resistance.

Supposing, for example, the resistance of the armature to be 3 ohms, and that of the field-magnets to be 2 ohms, then the total resistance is 5 ohms. When a current of 10 amperes is generated without any external resistance, the electrical power appearing in the circuit is equal to $C^2R = 100 \times 5 = 500$ watts, and if the current is increased to 20 amperes, then $C^2R = 400 \times 5 = 2{,}000$ watts.

Now, in both cases at least as much mechanical power is required to turn the armature as appears in the circuit as electrical power. A certain amount in excess is necessary (depending upon the efficiency of the machine), because some energy must be wasted in overcoming the mechanical friction of the bearings, &c., and still more by various electrical causes, such as eddy currents and the currents which flow in the coils during the period of short-circuiting.

The main point, however, upon which we desire at present to lay stress is that the increase in the current is not, and never can be, obtained without a corresponding increase in the power expended in turning the armature; in fact, from the above reasoning it is clear that in a series dynamo such as the one described, the mechanical power expended varies as the *square* of the strength of the current obtained in the external circuit, ignoring the mechanical power lost in the machine during conversion.

The ultimate strength of the current is, then, limited not only by the saturation of the field-magnets, but also by the amount of power at our disposal to drive the armature round. The engine, or other source from which the power is derived, must at least be able to furnish power equal to the maximum electrical power it is desired to obtain, to which must also be added that which is wasted in friction, &c.

With regard to the residual magnetism which is relied upon to start the current, it may be remarked that if the field-magnets are once strongly magnetised by a current passing in the direction in which it is desired the currents shall afterwards be generated, the cores will rarely lose all traces of magnetism, especially if of cast-iron. This sometimes happens, however, when the dynamo is moved, and the magnetism may even be reversed; but matters can easily be righted by passing a current, say, from a few cells for a moment in the proper direction through the field-magnet coils.

Hitherto, the dynamo has been considered as only working on 'short circuit'—that is, with the circuit completed without the introduction of any appreciable external resistance. In practice we require the current to do a greater or less amount of work in an external circuit, such as developing light in electric lamps or driving an electro-motor. In such a case, part only of the power is expended in overcoming the internal resistance (that is, the resistance of the armature and field-magnets) and maintaining the field, the remainder being employed in the external circuit. It is easy to find the relative amount of power absorbed in the two parts of the circuit. Thus, suppose the strength of the current be 40 amperes, and the total E.M.F. to be 80 volts, then the total electrical power is 40 × 80 = 3,200 watts. If, now, the difference of potential between the two extremities of the external circuit is found to be 60 volts, the power absorbed therein is 40 × 60 = 2,400 watts, for the strength of the current is the same in all parts of the same circuit. The remaining difference of potential is 80 − 60 = 20 volts, which is the fall along the internal circuit, and which absorbs, therefore, 40 × 20 = 800 watts. In this way, the ratio between the power spent in the external and internal portions of the circuit can in every case be measured. The two ends of the external circuit above referred to are called the 'dynamo terminals,' and the potential difference thereat can be measured by any convenient voltmeter. Since, also, the power spent in either portion can be calculated by multiplying the square of the curr strength by the resistance of the respective portions of the cir and as the current is the same in each, it follows that the e ıbsorbed in either part is directly proportional to the resistance of hat part. Thus, if the resistance of the external circuit is R ohms, ınd that of the dynamo r ohms, the total resistance is $\text{R}+r$. Let he total number of watts developed be W. Then, denoting the ratts absorbed in the internal and external parts of the circuit by r and y respectively, we have

$$x : y :: r : \text{R},$$
$$x : \text{W} :: r : \text{R}+r,$$
$$y : \text{W} :: \text{R} : \text{R}+r.$$

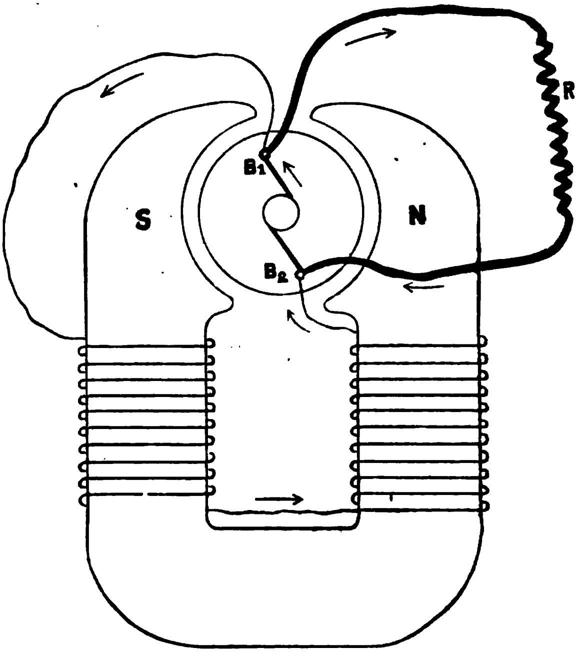
But it is very rarely that any dynamo works through an external circuit of constant resistance ; if it is supplying current to electric lamps, some of them are liable to be thrown into or out of circuit at any moment, and the behaviour of a series dynamo under these varying conditions must be briefly noted. Supposing the lamps to be joined up in series, then any addition to the number will increase the external resistance and reduce the current strength, and this means a corresponding decrease in the strength of the field, and, consequently, a further diminution in the current strength. If we suppose the lamps to be joined up in parallel, then any addition to the number in circuit decreases the total resistance and increases the current. This, by strengthening the field, still further increases the current strength. So that in either case considerable difficulties arise when a series dynamo is used on a circuit of varying resistance.

Moreover, this variation of the current, while it varies the effective fields of the armature and field-magnet, does not do so in the same proportion. The angle of lead must therefore be altered for every alteration of the current, or injurious sparking at the brushes will ensue.

For these reasons, the conditions under which the simple series dynamo can be conveniently employed are somewhat limited. For general work some method of 'regulation' is essential—that is, some arrangement by which the machine shall be made to develop just as much electrical power as the variations in the external circuit demand from it ; the first approximation thereto is obtained by a slight alteration in the manner of winding, giving us what is known as the 'Shunt' dynamo.

In the shunt dynamo the field-magnet coils, instead of being joined up in series with the armature and external circuit, are so connected that they form a 'shunt' *to the external circuit*, and receive, therefore, only a part of the current generated in the armature, the proportion depending upon the relative resistances. Fig. 159 shows the manner in which the connections are made,

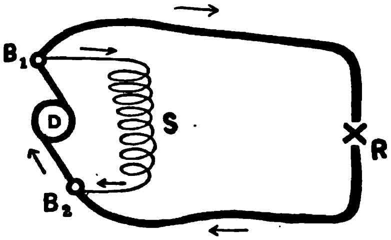
FIG. 159.



and the principle, which is very simple, should be readily grasped. The armature is rotated between the pole-pieces, and a certain E.M.F. is set up. The whole of the current generated passes, as a matter of course, through the armature, and we will suppose that its direction in both halves of the armature is upwards, or from the lower to the upper brush. At the upper brush, B_1, the circuit is divided, two paths being open to the current; one round the coils of the field-magnets, by taking which it augments and maintains the field; and the other through the external circuit, where it can be used to run lamps, or perform such other work as may be required. Both of these paths, however, terminate at the lower brush, B_2, and the quantity of the current which goes round either path is, as we have just indicated, simply inversely proportional to its resistance. In case any difficulty should be experienced in understanding the connections or in tracing the path of the current in the various branches, the arrangement is shown even more clearly in fig. 160, R being the external circuit, S the field-magnet coil, B_1, B_2 the brushes, and D the commutator of the dynamo.

The method of measurement applied to the series dynamo can also be adopted with the shunt machine, for the amount of power absorbed in the armature, field-magnet coils, and external circuit respectively, can be found by multiplying the current in that particular part of the circuit by the potential difference at its extremities. The armature resistance must be very low, otherwise, as it carries the whole of the current, the power absorbed therein becomes considerable; on the other hand, the resistance of the field-magnet coils requires to be relatively high. In an actual machine giving excellent results, the resistance of the armature is a trifle less than one-hundredth of an ohm, while the magnet coils offer 16·93ω, or about 1,700 times as great.

FIG. 160.



Supposing this machine were driven at such a speed as to develop an E.M.F. at the brushes of 100 volts, the external resistance R (consisting of a number of lamps in parallel) being half an ohm, then the current in the external circuit would be 200 amperes, and the power usefully employed therein 100 × 200 = 20,000 watts. The resistance of the shunt coils being 16·93ω, and the potential difference at the extremities 100 volts, the current produced therein will be almost 6 amperes. So that 6 × 100 = 600 watts will be absorbed in maintaining the field. The current in the armature of a shunt dynamo is the sum of the two currents in the external branches—viz. the field-magnet coils, and the external circuit, and in this particular case is 6 + 200 = 206 amperes. The armature resistance is 0·01ω, and since the fall of potential along it is equal to the product of current strength and resistance, the fall of potential along the armature from brush to brush is 206 × 0·01 = 2·06 volts. Therefore the power absorbed in it is 2·06 × 206 = 424·36 watts, which of course might also be obtained by multiplying together the square of the current passing through the armature by its resistance. Now the whole electrical power developed is 21,024 watts, of which number 1,024 are absorbed in maintaining the field and in overcoming the armature resistance, the remaining 20,000 being usefully expended in the external circuit.

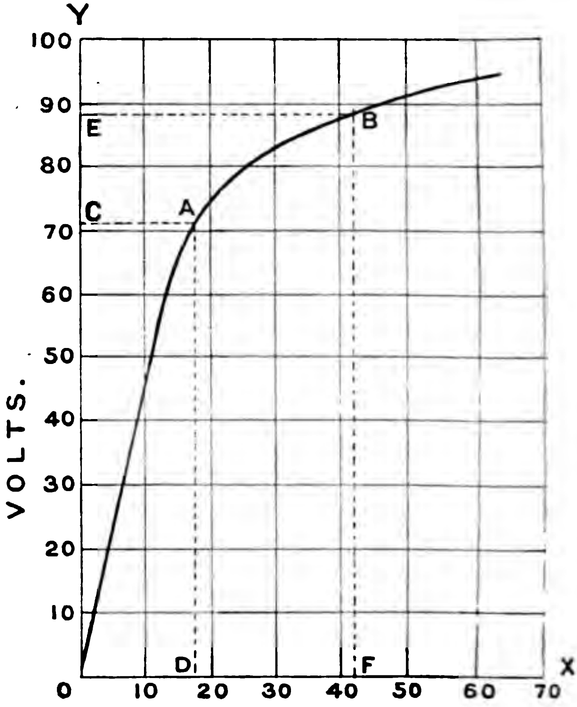
The ratio of the power usefully available to the total power developed is commonly known as the 'electrical efficiency' of the dynamo, and in the case just considered this ratio is $\frac{20,000}{21,024}$, or the electrical efficiency is slightly over 95 per cent. It is hardly necessary to point out that a very slight increase of the armature resistance would considerably lower this figure.

Ignoring for the moment the small amount of residual magnetism, it will be observed that in a series dynamo the field-magnets become demagnetised immediately the external circuit is broken, because the whole of the current is then stopped. In the case of a shunt dynamo, however, if the external circuit R in fig. 160 is broken, there is an alternative path left for the current generated by the armature, viz. round the field-magnet coil S. As the whole of the current will then pass through the field-magnet coil instead of only a portion of it, the strength of the field due to the field-magnet is always at its maximum when the external circuit is disconnected; exactly opposite to the case of the series dynamo. In the latter machine the most powerful current is generated and the field is strongest when its terminals are joined by a piece of thick wire; but this proceeding would have the reverse effect upon a shunt machine, because practically no current would flow round the coils on account of the very low resistance of the alternative path. And, although the shunt dynamo (especially if the resistance of its armature is low) is through a certain range less affected y changes in the external circuit than the series dynamo, neither f them is, for many purposes, sufficiently 'self-regulating,' or able o accommodate itself to these external variations. We may require dynamo to do one of two things: either (*a*) to regulate itself so as to send a *constant current* or a current of uniform strength through the external circuit, although the resistance may be considerably varied; or (*b*) we may require it to maintain a *constant potential* at the extremities of the external circuit—that is, at the brushes—under like variations of resistance. A machine cannot be constructed to fulfil both these requirements, and we will first consider the best of the many methods of maintaining a constant potential. This consists in the combination, in one machine, of the series and the shunt methods of winding. The simplest way, perhaps, of viewing the arrangement, is to consider the machine as a shunt-wound one, having added to it, round the magnet-limbs, a few turns of wire in series with the external circuit. Then, when the external resistance is made very low, and, as a consequence, the current in the shunt coils reduced to almost nothing, the magnetic effect of the series coils becomes a maximum, so that the opposite variations in these two sets of coils tend to keep the field more or less constant. It is clear that the success attending this combination will depend largely upon the proper proportions being given to the shunt and series coils, and in order to ascertain what these proportions are or should be for any particular case, we will now introduce a convenient method by which the variation of the E.M.F. developed by a dynamo under varying conditions can be studied.

Let us start with the case of a series machine, driven throughout the experiments at a constant speed, and joined up to a set of suitable known resistances which can be varied as desired. The resulting current can be measured by any suitable ammeter, and, the resistance of the machine and of the external circuit being known, the whole of the E.M.F. developed can be calculated as the product of amperes and ohms. We thus obtain the amperes of current flowing and the whole of the volts of E.M.F. developed, and these two quantities may be similarly found for any number of values which we choose to give the external resistance.

For instance, we might start with the external resistance very high and reduce it by suitable gradations until it becomes as low as safety to the machine will allow. A table might then be made showing the number of amperes flowing at every stage and the volts corresponding thereto. But by means of the 'squared paper' previously referred to, the whole of the experiments can be shown graphically

FIG. 161.



in the form of a curve, known as the 'characteristic curve' of th particular machine experimented with. Fig. 161 represents a curve, taken from a series machine, driven at a constant spe The volts calculated are measured off in vertical distances ordinates, and the amperes in horizontal distances or absc the intersection of *corresponding* ordinates and abscissæ being points on the curve. The length of the side of a square in the figure represents 10 volts or 10 amperes, but in practice it is better to use a larger sheet of paper divided into a greater number of squares, one side of each square representing 1 volt, or 1 ampere as the case may be. One of the experiments with this machine showed that 70·6 volts were developed when 18·2 amperes were flowing, and the point A on the curve is the result of this particular experiment. It is the point of intersection of the two straight lines, C A and D A, drawn at right angles to O Y and O X respectively, C A being 18·2 units and D A 70·6 units, in length (the unit being one-tenth of the side of one of the squares). Another experiment, which determined the position of the point B, showed that 42 amperes were flowing when 87·4 volts were developed; therefore the distance E B is made equal to 42 units, and F B to 87·4 units. Other points were fixed by similar experiments, and by joining these points together the curve was obtained. Considerable care must be exercised in performing the necessary experiments to determine one of these curves, and in the region of any decided change in the curvature the number of experiments must be greater than in the more uniform portions of the line. Notwithstanding, however, the exercise of the greatest possible care, some of the points are usually placed a little out of position, owing to experimental error. But experience and theory teach us that zigzag deviations never appear in the curves of dynamo machines, so that when the points do not lie exactly on a regular curve, we can, to a certain extent, correct experimental errors, by striking what may be called an average, with the aid of a flexible ruler.

Were the amperes and volts to increase in the same proportion throughout, the 'curve' would be a straight line; but with every self-exciting series dynamo we get a curve somewhat similar to the one here given—that is to say, with the first part ascending rapidly, then a decided bend, followed by a fairly straight portion making a smaller angle with the horizontal. It has already been pointed out that although the E.M.F. rises as the current flowing round the field-magnets (and, therefore, as the strength of the field) increases, a stage is reached when a given increase in the current does not give a proportionate increase in the field. This happens when the iron in the field-magnets becomes saturated, and it is at this stage that the decided bend in the characteristic curve shows that the amperes are increasing faster than the volts.

It sometimes happens that by merely glancing at a curve we can criticise the design of a machine in some important respects; for instance, the effect of having too little iron in a machine would be to make the bend occur earlier than it really should do. Other points of criticism will manifest themselves presently.

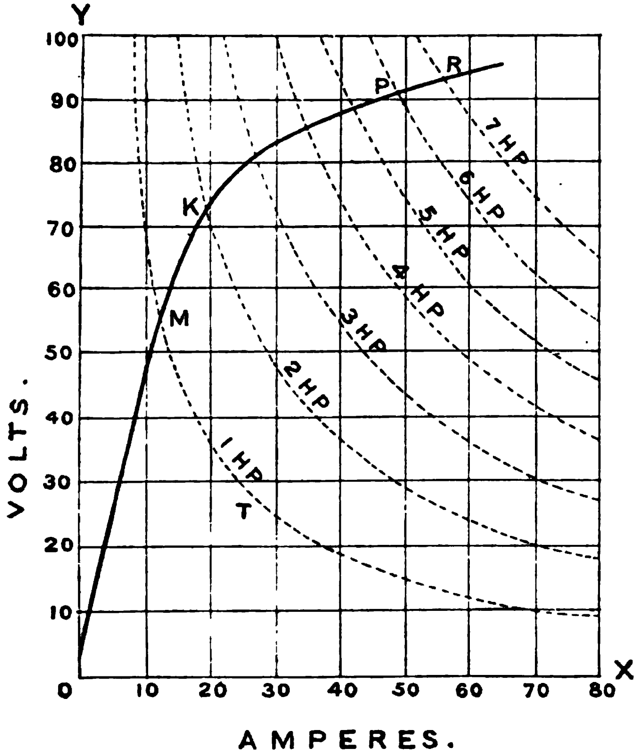
Reverting to fig. 161, it will be seen that the curve commences, not exactly at the point O, but at a point a little way up the vertical line, thus apparently indicating the existence of a small E.M.F. before the current commences to flow. This actually is the case, and results from the existence, in the field-magnets, of residual magnetism, which provides a weak field and produces a small E.M.F. at the terminals before the circuit is completed.

The two quantities—current and E.M.F.—plotted in this curve are those which, when multiplied together, enable us to estimate the amount of power being developed in the whole circuit, for the product of one volt and one ampere is one watt, which is the electrical unit of power, or rate of expenditure of energy, and 746 watts correspond to one horse-power. It follows that we can select any point on the curve and readily calculate what power was being developed in the circuit at the particular moment when the point was determined; for instance, during the experiment which determined the position of the point A, the power developed was 70·6 × 18·2 = 1,284·92 watts.

Such calculations can, in a measure, be avoided by the addition of another set of curves cutting the characteristic at points which correspond to a certain horse-power or fraction of a horse-power. Fig. 162 is a copy of fig. 161, with a number of the horse-power curves added in dotted lines. At the point M, where the characteristic cuts the 1 horse-power line, the product of volts and amperes is equal to 746 watts, while at K it is equal to 2 × 746 = 1,492 watts. Now, if the dynamo is driven at a higher speed the E.M.F. for a given current will be greater—that is, the vertical distances will be relatively greater than the horizontal ones as the speed is increased, and a curve somewhat similar in shape, but placed above the existing one, will be obtained. Several curves may thus be plotted on the same sheet of paper, and the power developed at different stages in each case readily compared, by reference to the horse-power lines.

Although it is possible to apply to these horse-power lines a ather high-sounding mathematical definition, they may be con-

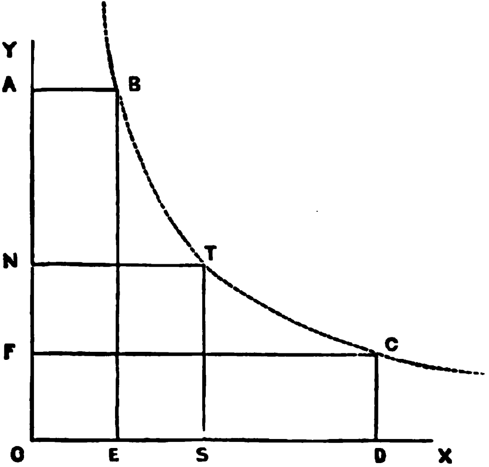
FIG. 162.



ucted by a simple process. As an example let us take the LP. line in fig. 162; T, the nearest point to O, will be equally tant from O X and O Y—that is to say, the perpendiculars drawn m T to O X and O Y will be equal. These perpendiculars are wn in fig. 163, where T S = T N, and their product T S × T N st be equal to 746 units, since T is a point on the curve.

Now NTSO is a square, all the sides are equal, and therefore $TS \times TN = TN^2 = ON^2 = 746$, or $ON = \sqrt{746}$. (The unit in fig. 162 is one-tenth of the side of a square, and in every case the unit is that length taken to represent one volt or one ampere.) If, therefore, we take ON and OS equal to $\sqrt{746}$—that is, 27·3 units in length, and draw perpendiculars from N and S, their intersection in T will give the first point on the curve. Then, if any convenient number of rectangles, equal in area to the square, be constructed, the product of two adjacent sides will equal $ON \times TN = 746$. For instance, the rectangles OB and OC are equal to the square OT (OA and OD being each twice the length of ON, and OF and OE being half that length). Therefore, since $AB \times BE$ and $CD \times OD$ are each equal to 746, B and C are points on the curve. This method illustrates the principle in a simple manner, and quicker methods of finding pairs of lines whose products are equal will suggest themselves (Euclid, III. 36). The side of the square determining the first point on the 2 H.P. line will be equal to $\sqrt{(2 \times 746)} = \sqrt{1492}$, consequently the other points can be found in the same way as before.

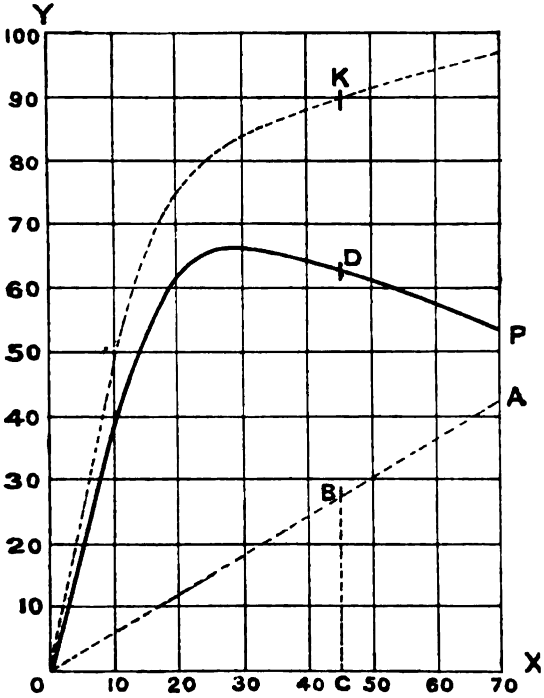
FIG. 163.



It will be remembered that the characteristic in fig. 161 was constructed by measuring the amperes, and calculating the total volts; but it is less troublesome to join up a voltmeter and measure directly the volts *at the terminals* of the dynamo, and then plot a curve showing the potential difference at the terminals (instead of the total E.M.F.), corresponding to various values of the current. In fact, this latter curve, usually called the external aracteristic curve, is the more useful of the two, for in practice is the external potential difference which concerns us most.

In fig. 164 the curve O P is the *external* characteristic, obtained m the same machine as the previous curve, running at the

Fig. 164.



e speed. The bend is now even more clearly defined; in fact, r a certain point, the potential difference falls as the current ncreased. One reason for this bending down is, as we have d, the magnetic saturation of the iron, and it is also partly sed by the heavy current in the armature distorting the field. e curve shows us then, at a glance, the particular current ngth at which we can get the maximum external potential erence at a given speed, and, of course, by inserting the horse-power lines, we can also see the amount of power absorbed in the external circuit. Now the remainder of the E.M.F. is absorbed in overcoming the resistance of the armature, and since this armature resistance is constant, this portion of the E.M.F. (found by multiplying the armature resistance and the current) will always be proportional to the current flowing. In fact, if we plot the 'curve' for current and E.M.F. expended in the armature, we get the straight line O A. And, further, if at any point, say C, we add together the vertical distance, C B, from the base line to the line O A, and C D, the vertical distance to the external characteristic, we get a line proportional to the whole E.M.F., giving the point K on the original total characteristic. In this manner we can construct the total characteristic curve, now shown as a dotted line; or, given this curve, we might draw the line O A, and by subtracting, deduce the external characteristic.

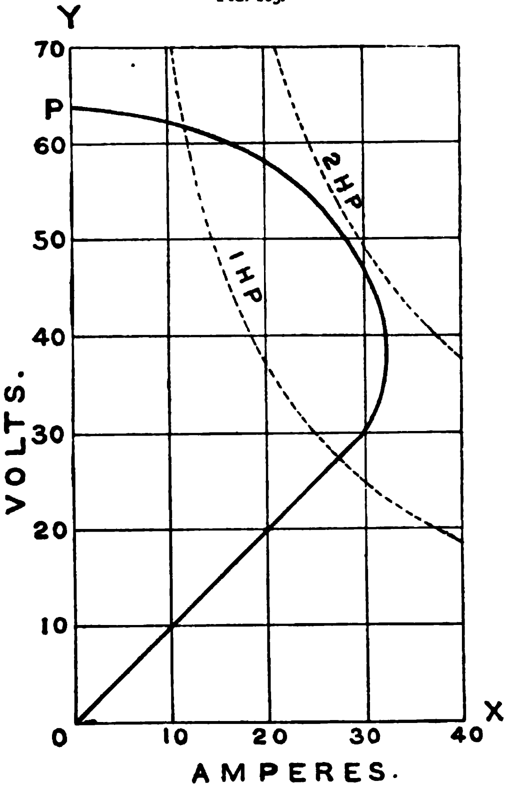
The greater the armature resistance the greater will be the fall of potential along it, and therefore also the greater will be the angle which O A makes with the horizontal. In fact, the tangent of this angle is proportional to the armature resistance, for

$$R = \frac{E}{C} = \frac{BC}{OC} = \tan BOC.$$

If this angle happened to be 45°, we should know that the armature resistance is 1 ohm, for the tangent of 45° is 1. In the present case the angle is 31°, the tangent of which is 0·601; therefore the armature resistance is 0·601 ohm.

Coming now to the case of a shunt-wound dynamo, if we plot the curve having ordinates proportional to the electromotive force, and abscissæ proportional to the current in the shunt coils, a somewhat similar result is obtained; but the 'external' characteristic is very different, as will be seen on referring to fig. 165, which is the curve obtained from a shunt dynamo, the vertical distances being proportional to the potential difference at the terminals, and the horizontal distances to the current in the external circuit. As before, the scale taken is such that a side of a square represents 10 volts or 10 amperes. If we suppose the series of measurements to be commenced when the external circuit is disconnected and its resistance therefore infinite, the E.M.F. at the terminals of the machine will have its maximum value, and we shall obtain P, the highest point on the curve. With this particular machine running at a certain constant speed, the maximum E.M.F. happened to be 63·5 volts, and as, of course, no current flowed in the external circuit, the point P is placed on the line O Y, at a distance of 63·5 units above O X. When very high resistance is introduced, so as to allow just a feeble current to flow in the external circuit, the E.M.F. at the terminals falls slightly, and continues to fall as the resistance is reduced and the current consequently increased. At first the amount of current abstracted from the field-magnet coil makes but little difference to the strength of the field, and therefore the E.M.F. falls but slightly. But when the external resistance is so low that the current becomes about 20 amperes, the amount abstracted from the shunt begins to have a very decided effect upon the strength of the field. The E.M.F. then falls considerably, and, the current remaining fairly constant during a small range, the effect is seen in the curve as a sudden bend downwards, almost, in fact, a perpendicular line. The resist-

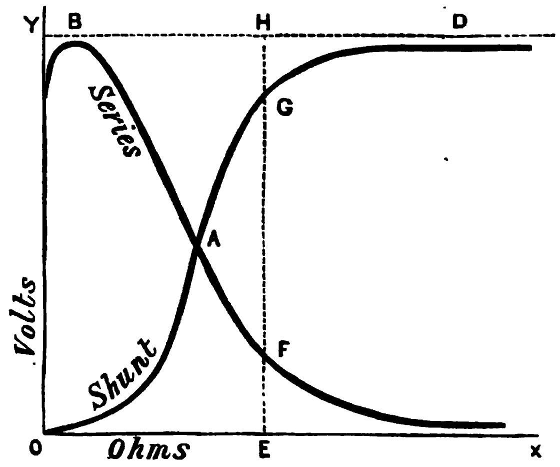
FIG. 165.



ance being still further reduced, not only does the E.M.F. fall, but also the current, giving the curve a turn ***backwards***, until presently the field-magnets lose their magnetism, and when the terminals are short-circuited the curve terminates in the point O, E.M.F. and current being then reduced to ***nil***. As the field-magnets, however, rarely lose the whole of their magnetism, a feeble current continues to flow after the terminals have been short-circuited, so that the curve should really end at a point some little distance from O along the line O X.

Although these characteristics give us a clear idea of the manner in which the external potential varies with the classes of dynamos referred to, we can better understand the method of combining, or, technically speaking, 'compounding,' the series and shunt windings to obtain self-regulation, by constructing and comparing other curves, which show how the external potential and the external resistance vary together, both in a series and in a shunt machine. As before, the ordinates (fig. 166) represent volts, but the abscissæ now represent ohms. The figure shows two curves, one for a shunt and the other for a series machine, both starting at or near the line O Y, when the external resistance is very low.

FIG. 166.

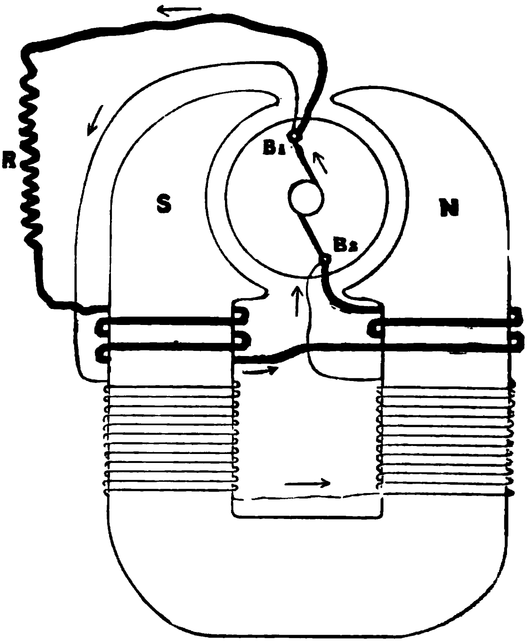


In the case of the shunt machine, the curve shows the E.M.F. to be very low at first, gradually rising for a short distance as the resistance is increased, until at a certain stage it ascends suddenly, this, as we know, occurring when the external resistance is great enough to allow the field-magnets to become strongly magnetised. On the other hand, the curve from the series machine is at its highest point B, when the resistance is low, and it falls almost in the same manner as the other curve rises. This curve can hardly start on the line O Y, because, of course, when the resistance between the terminals is *nil*, no difference of potential can exist, but it quickly reaches the highest point as the resistance is increased. Now if in one machine it is possible to so proportion the shunt and series windings that the maximum effect of the series coil is equal to the maximum effect of the shunt coil, and also that the effect of the series coil diminishes in the same proportion as the effect of the shunt coil increases, these two windings will counterbalance each other through a considerable variation of resistance, and the result will be a constant external potential difference. The first condition would make the height of the highest points on each curve equal; while if the second condition were attained, the slope downward of the one curve would exactly correspond to the slope upward of the other. And at any point, such as E, the E.M.F. due to the series coil added to that due to the shunt coil, that is, E F + E G, should give us the vertical line E H equal to the height of the highest point on each curve. Likewise, the point of intersection A should be midway between B D and O X, and the heights of the two curves added together throughout should produce the straight line B D. Then the E.M.F. at the terminals being constant, the current will vary regularly with the resistance, and we shall consequently obtain a straight line for the characteristic curve of the compound-wound machine. It is evident that if the series coil acts too powerfully the effect will be to raise the point B, that is, to make the E.M.F. higher when the external resistance is low and the current strong, than when the external resistance is higher; and *vice versâ*.

Since, however, the effect of an alteration of the speed of rotation of the armature is so different in the case of a series as compared with a shunt machine, a dynamo compounded in the manner just described is only self-regulating at a given speed ; for at any other speed the two windings do not compensate each other.

In the case of a series machine, if, for instance, the speed were doubled and the external resistance increased sufficiently to keep the current the same, the strength of field would remain unaltered and the E.M.F. would be increased almost, but not quite, two-fold :

FIG. 167.

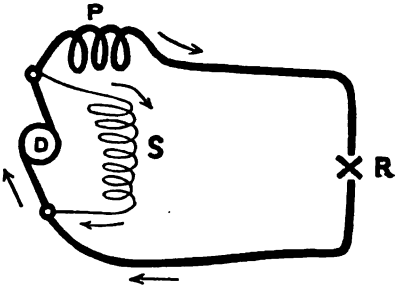


by the doubled speed. On the other hand, if, with a s dynamo, by increasing the external resistance we maintain external current constant when the speed is doubled, the curre the shunt coil, and therefore the strength of the field, incre instead of remaining the same as does that of a series dy While, if at the doubled speed the resistance were reduced to the current in the shunt coil the same as at the lower speed, external current would be greatly increased in strength. The ecause of these different effects of an alteration of speed on the eries and shunt windings, the dynamo will only regulate perfectly hen driven at the particular speed for which it was compounded. n practice the speed at which the machine is to run is usually determined beforehand, then at this speed the shunt coils alone must e able to provide a sufficiently strong field to develop at the terminals the required E.M.F. when the external circuit is disconnected, while when the external resistance is made as low as it will be in actual working the ampere-turns in series should be able to maintain this same field.

The connections of a compound-wound dynamo, and the paths taken by the current through its coils, are typically illustrated in fig. 167.

As in previous similar figures, B_1 B_2 are the brushes; at B_1 the current generated in the armature divides, part going through the shunt coils wound on the lower parts of the limbs of the field-magnet and thence returning to the brush, B_2. The remainder passes through the external circuit R, then round the series coils on the upper part of the field-magnet, and thence to the brush, B_2. The shunt coils are wound with comparatively fine wire, but, of course, the resistance of the series coils must be kept very low as they carry the main current, and they are composed, therefore, of a few turns of very thick wire. The relative positions of the two sets of coils is not always that shown, the series coil being sometimes wound outside and sometimes inside the shunt coil; but this not very important point is decided by convenience in construction rather than by theory.

FIG. 168.



To render the path of the current even more easily understood, fig. 168 is added; R is the external circuit, D the armature, S the shunt coil, and P the series coil.

In practice so successful are designers and manufacturers, that it is not uncommon to find a machine which, when driven at its proper speed, gives a straight line as its characteristic, through a range of 100 amperes or even more.

The foregoing method is the one commonly adopted for compounding dynamos to give a constant external potential, notwithstanding variations in the external circuit. We shall not refer to any other methods, many of which are only theoretically possible but may briefly mention some interesting experiments of the Dr Hopkinson which bear somewhat upon this point. They disconnected the field-magnet coils of a certain machine, and, havi placed the brushes in the position for an undistorted fie connected them to the terminals of a Siemens dynamome Then, when the armature was driven at 1,380 revolutions p minute, the current, due solely to residual magnetism, was amperes; but on giving the brushes a slight forward lead, current fell almost to zero, because the field due to the curren the armature was then opposing that maintained by the resid magnetism. But when a backward lead was given to the brush the polarity of the armature was shifted round so as to enh the residual magnetism in the pole-pieces; the armature, in f now generated its own field, and a current of 234 amperes obtained. Since the field in such a case is almost proportion the current flowing in the armature, which increases as the exte resistance falls, such an arrangement would regulate for cons potential; but it is not practicable owing to the destructive sparki which arises in consequence of the coils being short-circuited the brushes while fairly active.

CHAPTER X.

ECT CURRENT DYNAMOS—*continued.*

illustrate and describe some of the best modern
ynamos, selecting only such as are of first-class
truction, and directing attention in each case to
ich are likely to prove most instructive in showing
l principles are applied, and how, in practice,
d economical considerations sometimes cause a
forms which a narrow theory might show to be the

it is recommended to pay particular attention to the
ied for securing mechanical strength and durability.
erved, for example, that it is quite as important to
conductor being stripped from an armature, as to
ulate it. Again, while a waste of power, such as is
the heating of the iron core by eddy currents, is to be
ny waste which shows itself in such a manner as the
g of bearings is equally, or even more, to be avoided.
s the power applied to the shaft is wasted—in the
after, and in the latter case before, it has been trans-
electrical power.

illustrates a dynamo constructed by Messrs. W. T.
Co., the armature being of the Gramme ring[1] type,
ld produced by an inverted horse-shoe magnet. This
machine is compound-wound, and the arrangement is
milar to that depicted in fig. 167. A vertical section of
e at right angles to the shaft is given in fig. 170. The
of cast-iron and includes a solid piece, D, in the
ctly under the armature and field-magnet, to form the

---

[1] of this type of armature is now made much longer than formerly
re is frequently and more aptly called a cylinder armature.

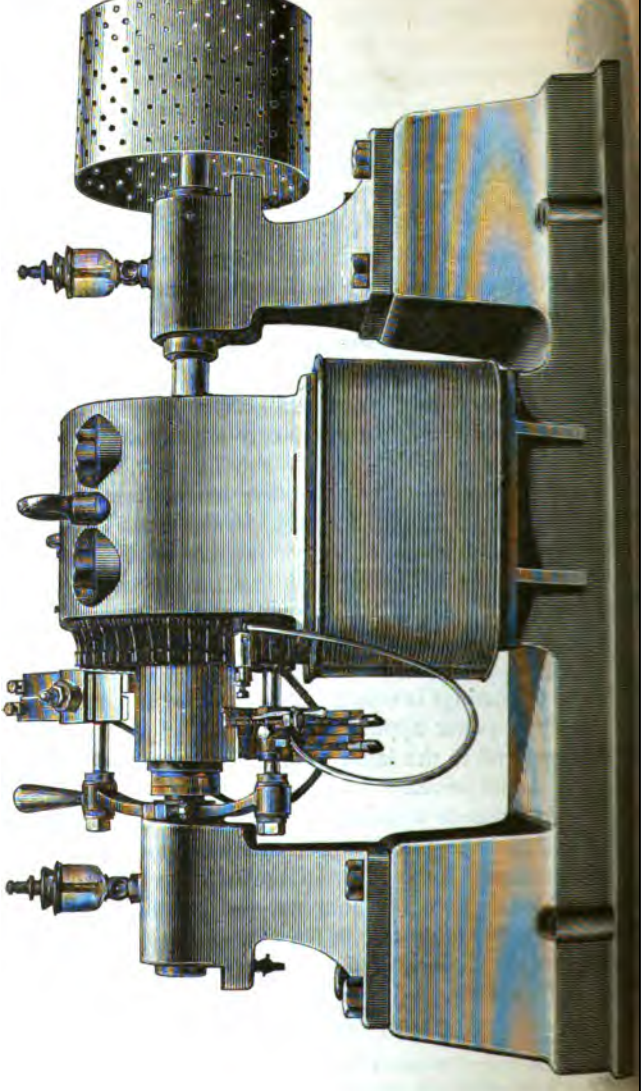
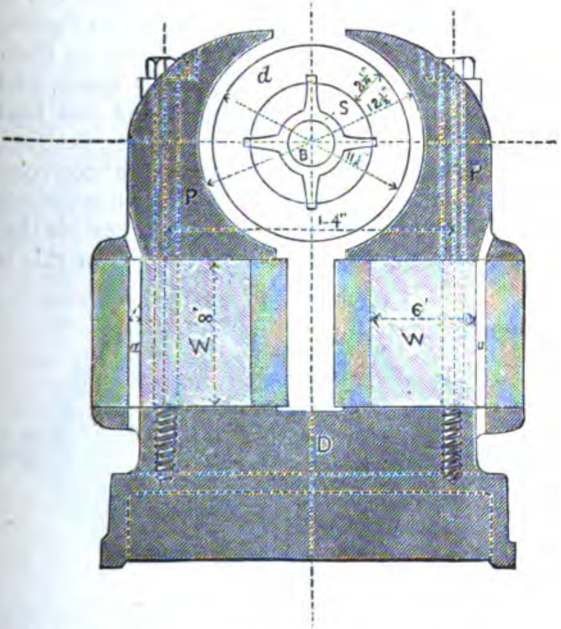


FIG. 169.

yoke of the latter. But wrought-iron is employed for the actual cores round which the field-magnet coils are wound, each core, W W, consisting of a slab of special soft hammered scrap-iron; thus giving the advantage, previously referred to, of economising copper wire, by obtaining the requisite magnetic conductivity with the minimum sectional area. The pole-pieces are of grey cast-iron, and the sectional area of all the cast-iron portions is sufficiently increased to compensate for the lower permeability as compared with that of the excellent iron forming the core. It is, however, evident that as the lines of force begin to pass into the armature from the bottom of the pole-pieces, fewer lines pass through the upper part of it than through the lower, and consequently there is no advantage in having the same thickness throughout. The pole-pieces, P P, are therefore so

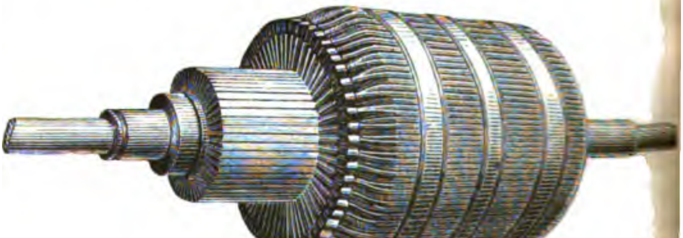
FIG. 170.



shaped that they taper away towards the horns at about the same rate that the number of lines of force passing through them diminishes in consequence of the lines leaving at the various portions of the face, thus giving the same magnetic density throughout. Two long bolts pass through each of the pole-pieces and the wrought-iron cores, screwing, at their lower extremities, into the solid portion of the bed-plate which forms the yoke-piece, and thus holding these parts firmly together. The coils are wound so as to leave a space between the wire and the outer face of the wrought-iron core, as shown at *a a* in the figure, forming thereby a very effective means of ventilation, for as the wire gets warm its heat is imparted to the air inside this space, and this air rising, a constant circulation is maintained and the heat carried off by a steady draught of cold air.

The series winding consists of twenty-five convolutions of copper strand, composed of nineteen No. 15 wires (standard gauge), a stranded conductor being much more flexible than a s one, although it occupies a little more space. Over this is wou

FIG. 171.



the shunt coil, which consists of 2,712 turns, its resistance be 20·6 ohms. In order to afford a means of obtaining this res ance with this particular number of convolutions, two siz wire are employed—viz. Nos. 15 and 16, S.W.G.—the respec lengths of these two wires being adjusted to satisfy the condit

The complete armature is shown in fig. 171. The core co sists of a number of very thin flat rings of well-annealed char iron, as shown at *d* in the sectional view (fig. 170). The ou diameter of the ring or disc is 11½ inches, and its inner diam

¼ inches. Four rectangular notches are cut out of each disc, at qual distances round the inner edge ; a sheet of thin paper insuates each disc from its neighbours, the whole of them being held ightly together by two rigid end-plates. Upon the Bessemer steel haft B is keyed a gun-metal spider, S, having four radial arms, its ength along the shaft being equal to that of the finished core, and the extremities of the arms fitting accurately into the notches in the discs. The student will remember the necessity for avoiding, as far as possible, the use of iron in the interior of a Gramme ring, and will therefore understand the reason for making the spider of gun-metal. It should also be borne in mind that although it is absolutely necessary to efficiently insulate the thin plates into which the core is divided, yet, in consequence of the thinness of the discs, the space occupied by the insulation forms a considerable portion of the whole, whence the magnetic resistance is proportionally increased. In this particular case, 80 per cent. of the core consists of iron and the rest of paper.

The armature conductor consists of cotton-covered copper wire of No. 9 standard wire gauge, lying round the core in one layer and offering a resistance, from brush to brush, of 0·048 ohm.

There are two convolutions in each section, the adjacent ends of neighbouring convolutions being soldered to radial lugs projecting from the commutator bars, as shown in fig. 171.

There are 152 such sections, and, consequently, seventy-six bars in the commutator, these bars being of hard drawn copper insulated from each other by mica strips 0·75 mm. in thickness. Mica is almost the only material now used for this purpose, for which it is eminently suitable, because of its excellent insulating properties, its great durability, and its practically perfect cleavage, in consequence of which it can be procured of any desired thinness.

As the length of conductor parallel to the shaft is considerable, there is a risk of its bulging out when rotated at a high speed, a tendency which would be assisted by the rise in temperature and consequent expansion of the wire, caused by the current itself. Any such bulging out or stripping of the conductor is prevented by binding the armature with several turns of fine strong wire in three places, as shown in fig. 171.

The speed of the machine is 1,050 revolutions per minute, at which it is capable of giving a current of 75 amperes, with an E.M.F. at its terminals of 100 volts.

The brushes consist of flat tough copper strips, fixed in adjustable holders, which are carried by the horizontal arms projecting from the rocking lever, as shown in fig. 169. This lever is provided with an insulating handle, by means of which it can be rotated in either direction round the axis of the shaft, thus affording facilities for altering the lead of the brushes to suit the requirements. It is carried on a projection from the standard supporting the bearing, and is made in two pieces bolted together, so that it can be readily tightened up on its bearing, or, if necessary, removed. The horizontal arms are insulated from the lever by hard fibre collars; and spiral springs, with adjusting screws, are provided for varying the pressure of the brushes on the commutator, the pressure being always as light as is consistent with reliable contact.

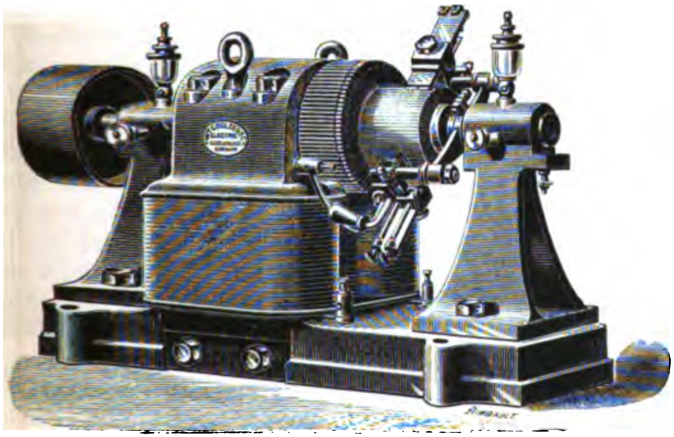
The brushes are shown lifted from the commutator; and it be observed that they can be adjusted along the bars, so as press upon different parts when the machine is running, thereby distribute the wear. The commutator is turned up perfectly true in a lathe with a fine tool which cuts the copper cleanly and does not drag or burr it over the mica strips.

The shaft-bearings are of phosphor bronze, and the rim of pulley is perforated to afford a better grip for the belt.

Most machines are, however, now made of the drum type, fig. 172 illustrates a drum-armature dynamo constructed by the makers. The general proportions of the field-magnets are somewhat similar to those of the machine already described, but method of fixing the parts together differs. The two vertical passing through each of the pole-pieces extend only about way into the wrought-iron cores. Each core is lengthened a and, fitting into a slot in the cast-iron bed-plate, is held firmly position by two horizontal bolts passing through the solid the casting. The core is built up in a manner somewhat to that adopted for the ring machine, but the radial depth of discs is somewhat greater, and the driving-spider is made of instead of gun-metal. The armature conductor is composed vo No. 11 wires wound on together in parallel, and the resistance om brush to brush is 0·0341 ohm. The commutator has eighty ars. The field-magnets are compound wound, the series-winding omprising sixty-six turns, each of which consists of two No. 6 rires in parallel; and the shunt coils, which are wound over the eries coils, contain 2,600 convolutions of No. 15 wire, having a esistance of 15 ohms.

At a speed of 1,180 revolutions, a current of 85 amperes, vith a potential difference of 80 volts at the terminals, is delivered.

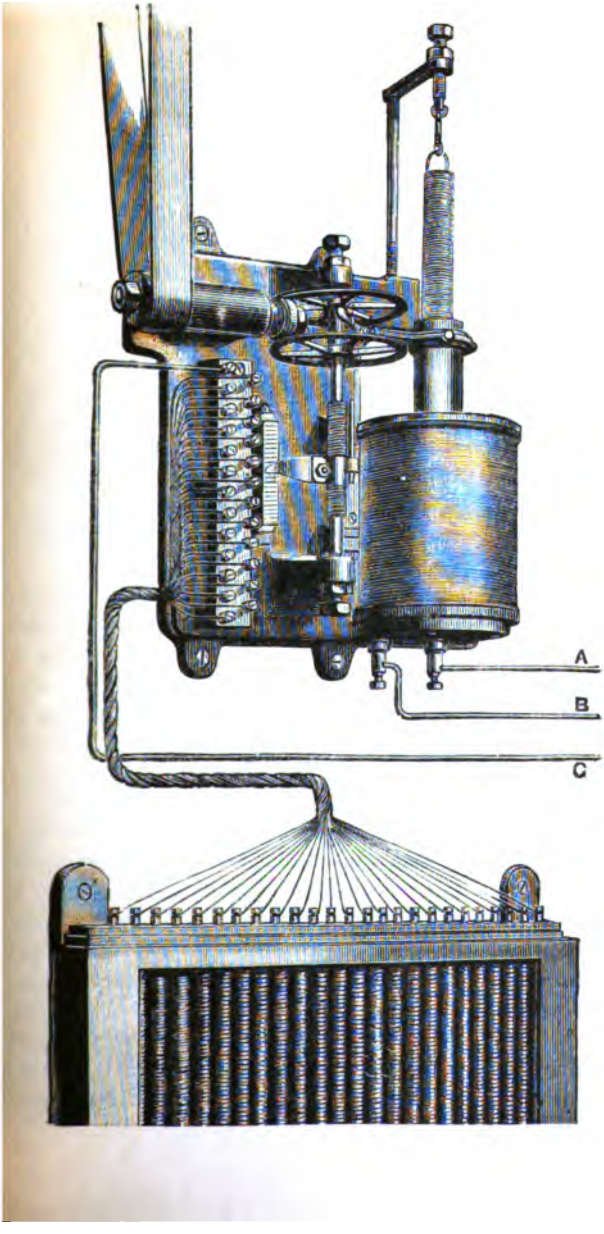
FIG. 172



In some cases, where the current generated is very heavy, the active conductor consists of thick copper bars, which are laminated to reduce the eddies in them, the bars being, as a rule, divided longitudinally into five sections.

These dynamos are compounded to give a constant potential when driven at a certain speed, but for cases where the speed is liable to variation, and where, therefore, a compound machine cannot be used, but where a constant E.M.F. or a constant current is required, or where it is desired to maintain a constant current although the external resistance varies, an automatic mechanical regulator is employed. This regulator varies the strength of the field by altering the strength of the current flowing through the field-magnet coils. A set of resistance coils is placed in series with the field-magnet coils of a shunt-wound machine, and an arrangement adopted for cutting out some of these coils when the current or the potential difference falls too low, or inserting more of them when it becomes too high. The complete set of regulating apparatus is shown in fig. 173. The resistance coils, which are shown at the lower part of the figure, consist of spirals of bare iron wire, supported by a wooden frame in such a manner as to afford great facilities for cooling when heated by the passage of the current. An important part of the apparatus is the large solenoid, placed with its axis vertical. If it is desired to maintain a constant potential under varying conditions, this solenoid consists of many turns of fine copper wire, the two wires A and B leading from its terminals, being joined to the brushes of the dynamo. An iron core, suspended by a spiral spring, projects a short distance into the upper portion of the solenoid. When the potential rises the current increases and sucks this core further down; while a fall of potential allows the antagonistic spiral spring to withdraw the core a little. From the upper portion of the core projects an arm, its end playing between two light wheels which are rigidly fixed on a common vertical spindle, this spindle having a small amount of end-play. The tension of the spring is so adjusted that when the potential is at the required value the upper wheel just rests upon the arm projecting from the core, and both wheels are kept clear of a small rubber-faced disc on the end of a short horizontal shaft, which is driven by a belt from the main shafting. If, on account of a rise in the potential, the core with its projecting arm is sucked down, the two light wheels drop, and the upper one engaging with the rubber disc, is rapidly rotated. A screw thread is cut in the vertical spindle some little distance below the wheels, and on it is a rather long screw-nut which is prevented rotating, and which, therefore, travels up or down according to the direction of rotation of the vertical spindle. A spring projects from this nut, its end passing over a set of contact pieces to which are connected the various resistance coils, one end of the series of coils being joined to the upper contact piece, and the other end direct to the vertical spindle and screw nut, which are also in connection with the terminal B. The arrangement

FIG. 173.

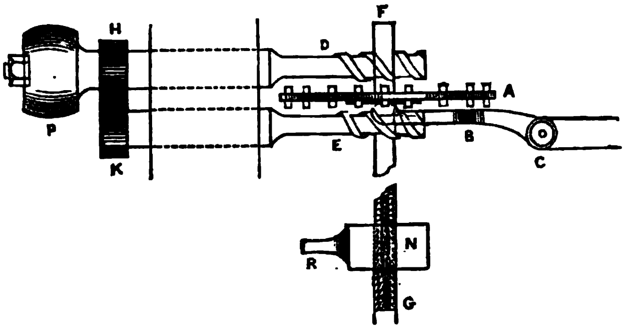


such that the motion imparted to the spindle, due to an increase of E.M.F., moves the flat spring in the direction which throws more resistance in series with the field-magnet coils, while if the core is moved upwards, the lower wheel engages with the friction disc and rotates the spindle in the reverse direction, reducing the resistance in the field-magnet circuit.

The solenoid is subject to the same heating error as a voltmeter, and to minimise this it is more frequently wound with fairly thick wire, the temperature of which rises but little, and the necessary resistance is obtained by joining in series with it German silver coils, which have a lower temperature coefficient, and, being left bare, dissipate heat readily. When the apparatus is required to maintain a constant current, the solenoid is wound with thick wire, and is joined up directly in the main circuit; the rise and fall of the main current which passes through it acting in the same way as a rise and fall of potential at its ends. The small horizontal shaft is driven at about 400 revolutions per minute, and the nut carrying the contact spring can then travel over the whole range in about ten or twelve seconds. The flat spring is so broad that the circuit is never broken during the movement of the spring, and a large number of coils is employed in order that the increase or decrease of the resistance shall take place gradually. The weak point about the apparatus, as depicted in fig. 173, is the means adopted for imparting circular motion to the light wheels; for, although the friction between the rubber disc and the wheel rim is at first quite sufficient, it becomes uncertain and unreliable if the rubber gets dirty or covered with oil. To overcome this difficulty an entirely different gearing has been adopted in the later apparatus, the essential parts of which are shown in fig. 174. R is the contact spring, carried by the nut N, working upon the screw shaft G, up and down which the nut travels according to the direction in which the screw is turned. The screw forms the lower part of the vertical spindle F G, upon the upper part of which is fixed a pin-wheel A, that is, a flat disc having a number of pins fixed parallel to its axis at equal distances round its circumference. Behind the spindle and parallel to the plane of the disc are two endless screws D, E, the upper one being at the end of the shaft, which is driven by a belt on the pulley P. By means of he equal spur wheels H and K, the lower shaft is driven at the ame velocity as the upper one, but in the opposite direction. The arm projecting from the top of the core of the solenoid is ivoted at C, and forked from the point B, the adjustment, as efore, being such that when the current or potential is at its roper value, the pin-wheel rests on the extremities of the fork, ust midway between the two revolving screws. Any movement of he core raises or lowers the supporting arm, thus lifting the pin-heel or allowing it to fall, so that the pins then gear either with he upper or the lower screw, and communicate a circular motion the vertical spindle, in the one direction or the other as the se may be.

Within certain limits, the E.M.F. or current which the regulator aintains can be varied by altering the tension of the spiral spring g. 173), and as this spring is a very important factor in the ooth working of the apparatus, considerable care is exercised in ecting it. In order to render the core perfectly astatic, resting cidedly in any required position, it is necessary for the pull of solenoid on the core and the antagonistic pull of the spring to lance each other, length for length, throughout the whole of space travelled by the core—that is to say, suppose it ex-iences a sucking force which moves it two centimetres inwards, inst the spring, the force of suction on the core in this new ition must be greater by exactly the same amount that is neces-y to extend the spring two centimetres. This rather difficult

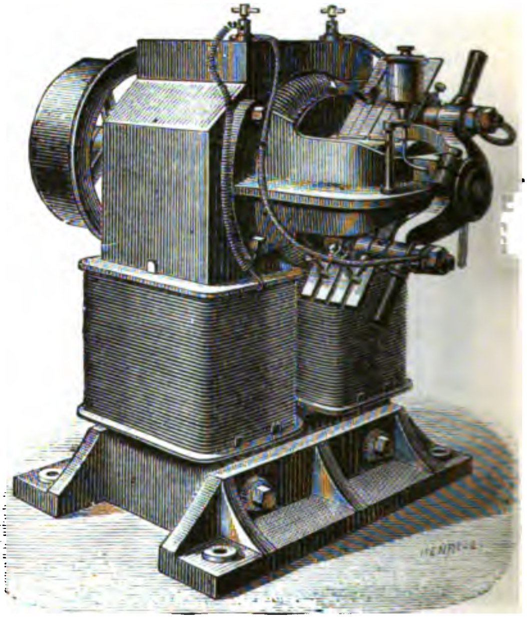
FIG. 174.



adjustment is so successfully accomplished that the core is perfectly astatic, gliding to any new position immediately the current changes, and floating there without any oscillation.

The 'Phœnix' dynamo is made by Messrs. Paterson & Cooper, and in two distinct forms, according to the circumstances under which the machine is to be employed. Where lightness of construction is imperative the field-magnets are made of wrough iron, but where the weight becomes a matter of secondary impo ance cast-iron is used, its lower permeability being compensa for by using about two and a half times the amount of metal. T first of these machines, in which the aim has been to obtain comparatively great electrical output for a minimum weight. illustrated in fig. 175.

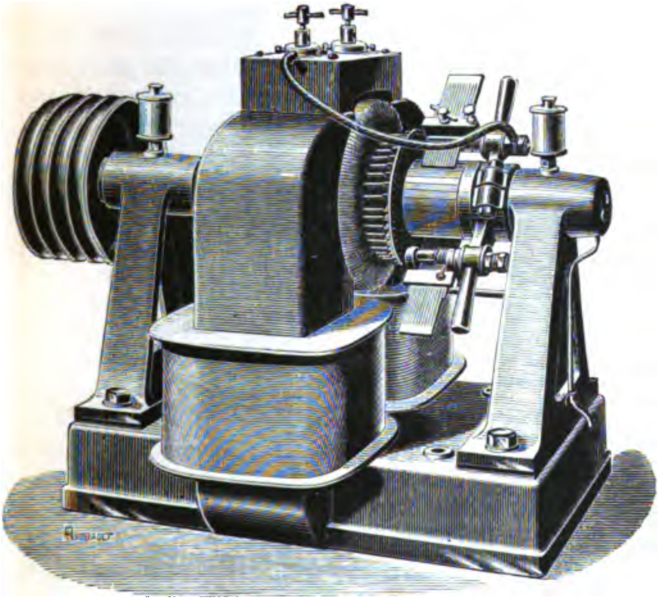
FIG. 175.



The field-magnet and bed-plate are the parts of the machine in which the greatest reduction in weight can be made, and skill of the designer is shown in the manner in which this is accomplished without increasing the 'magnetic resistance' or diminishing the mechanical strength.

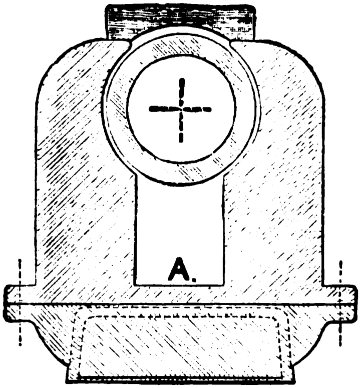
The field-magnet is of the horse-shoe shape, fixed with the poles uppermost. It is made of a single massive wrought-iron forging, which is slotted out to form the two limbs, sufficient metal being left at the bottom to form a substantial yoke. The space in which the armature revolves is then bored out. It will thus be seen that there is no break in the magnetic circuit, while, being of wrought-iron, the magnetic resistance is very low. Two cast-iron angle-pieces, which receive the foundation bolts, are bolted on to the yoke. The bobbins on which the field-magnet coils are wound are made of sheet-iron, with brass flanges, and are slipped over the limbs after the wire has been wound.

Fig. 176.



Two very strong gun-metal brackets are then bolted to the pole-pieces, for the purpose of carrying the armature bearings, which are of white metal, the whole forming a machine mechanically strong, but of comparatively little weight. It need hardly be said that this construction is expensive, and would not be warrantable in cases where there is a solid foundation available and where a little extra weight is immaterial. Fig. 176 illustrates a machine designed for use in such cases, a section through the field-magnets being shown in fig. 177. Here the field-magnets are of cast-iron, but of greater sectional area. Both limbs are in one casting, being connected together by the rather thin piece shown at A. This casting is securely bolted down to the cast-iron bed-plate, which, directly underneath the field-magnet, is solid and massive, and, together with the thin connecting-piece A, forms the yoke. The terminal board is fixed across the upper ends of the field-magnet cores. The bobbins are similar to those in the machine previously described, but the armature is carried on vertical cast-iron brackets bolted to the bed-plate. In the machine shown the pulley is grooved for rope-gearing.

FIG. 177.

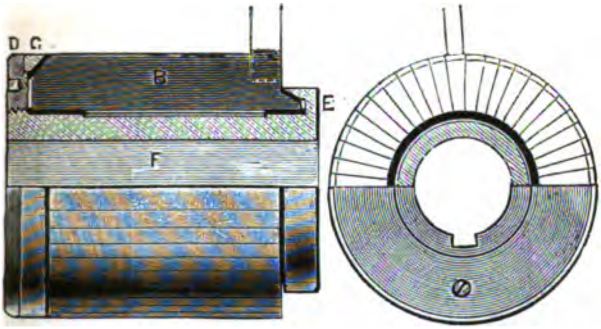


The brushes are made of soft brass wire, and in the wrought-iron machine each brush is composed of four independently adjustable sections, the holder rocking round an extension of the gun-metal bracket.

The commutator consists of forty-eight bars, either of hard drawn copper or gun-metal castings, insulated with mica. Fig. 17[illegible] gives two views of this commutator, the upper half in each case being shown in section. Upon the steel shaft F is keyed a gun-metal bush, E, with a rim at one end recessed to receive the projections from the commutator bars B. The opposite corner of these bars is shaped to fit a steel ring, C, of triangular section, which is held tight home by the wrought-iron washer, D, screwed on to the gun-metal bush. The bars are insulated from each her by means of mica, and from the bush E and ring C by sheets white fibre, indicated by the thick lines in the figure.

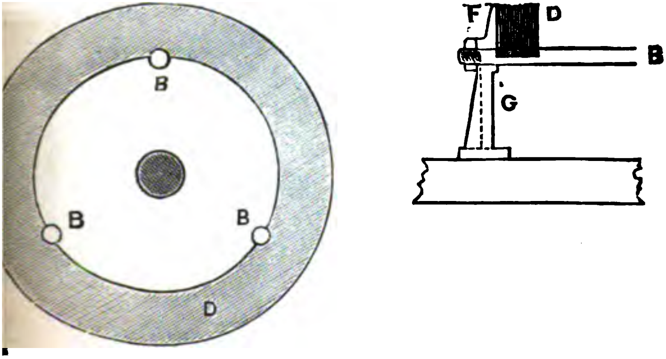
The armature is of the ring type, and its core is built up of a mber of thin soft iron rings (D, fig. 179), insulated by paraffined

FIG. 178.



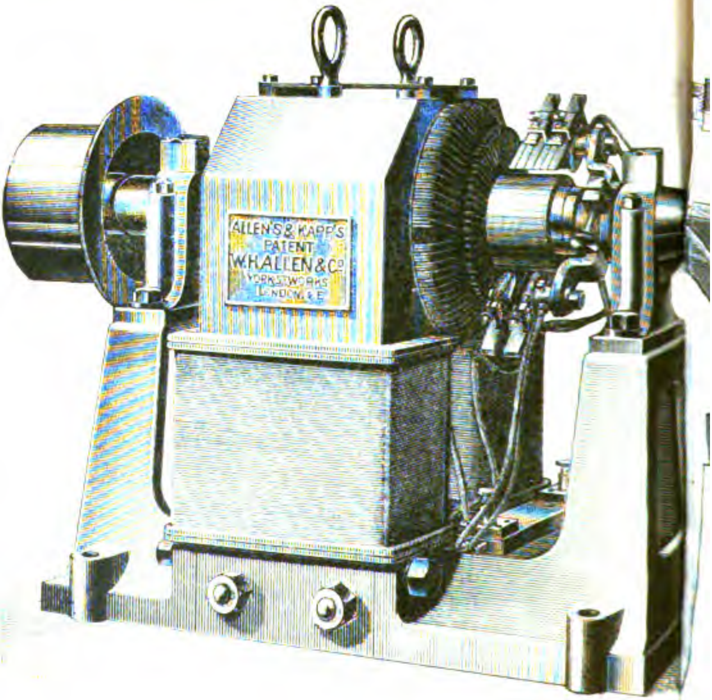
er, and the whole firmly clamped together between two end nes by three delta metal bolts, B, semicircular pieces being mped out of the iron rings to fit these bolts. A gun-metal

FIG. 179.



ler with three radial arms, G, is keyed on to the shaft at each of the core, the bolts passing through their extremities as at F. One size of the machine illustrated in fig. 176 has an output ,500 watts at 100 volts (65 amperes) when driven at 1,300 revolutions per minute. It is compound wound. The resistance of the armature is 0·03 ohm, and of the shunt coil 20·8 ohms the series turns being wound inside the shunt coil and having resistance of 0·018 ohm. From these figures the student ca calculate the power spent in the various portions of the circu when the maximum current of 65 amperes is flowing.

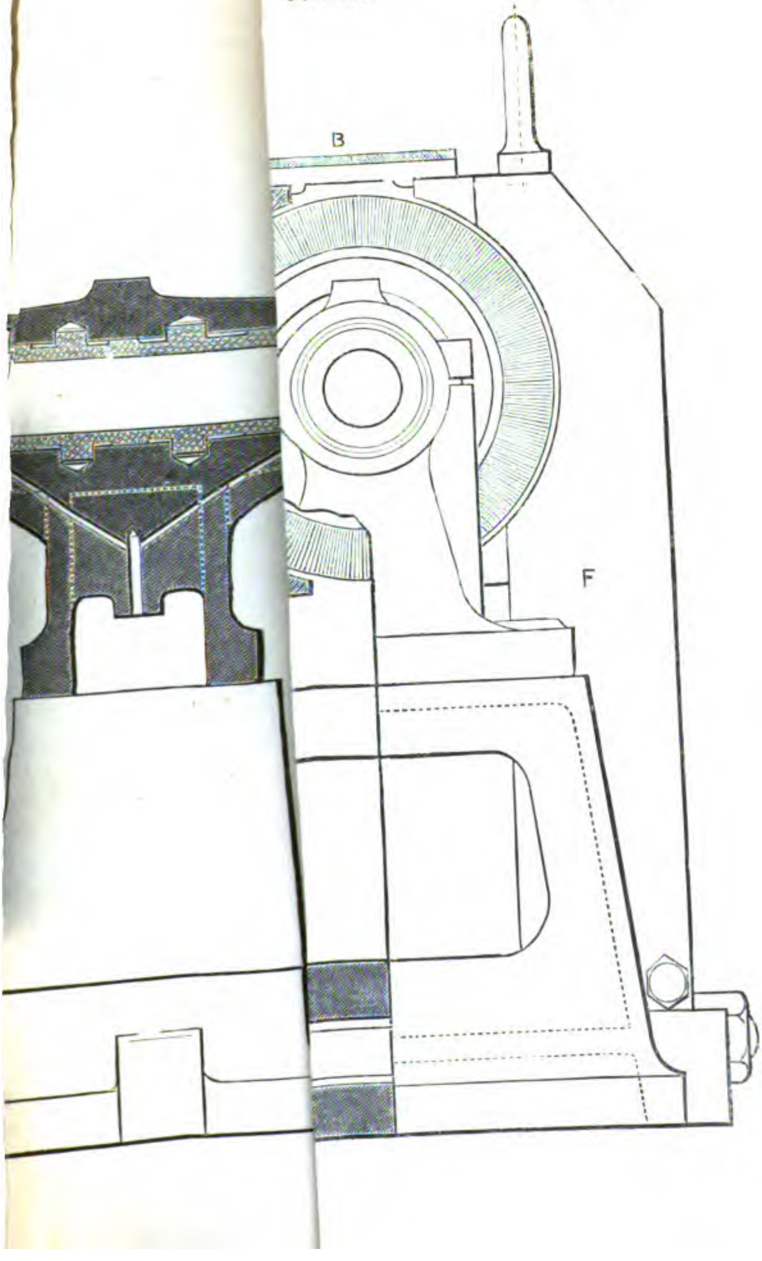
Fig. [illegible]



A general view of the dynamo designed by Mr. Gisb and constructed by Messrs. W. H. Allen & Co. is given in fig. The field-magnets are also of the inverted horse-shoe ty which, it should be mentioned, Mr. Kapp was the first to

FIG. 182.

To face p. 332.



object being to minimise, as far as possible, the magnetic leakage, as will be further explained presently. The armature in the machine illustrated is of the ring or cylinder type, but very few Kapp machines are now made with this class of armature. The drum and ring types are, however, very similar in external appearance, the chief difference being that due to the greater projection of the drum armature on account of the space taken up by the cross-connections.

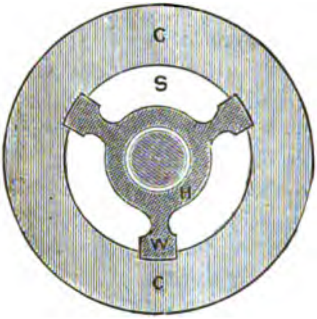
Figs. 181 and 182 illustrate many details of a recently-constructed drum machine, the former being a longitudinal section, and the latter an end view, half in section.

Each field-magnet limb, F, consists of a single slab of wrought-iron, the lower end of which fits into a slot in the cast-iron bed-plate. The bed-plate is solid at this part, and the vertical limbs are secured in position by two large bolts passing through, as shown in fig. 182. The pole-pieces are bored out circularly to form the space in which the armature is to revolve, and the horns *a a* securely pinned on. Upon the upper horns is fixed a board B, which acts as a cover to protect the armature. The field-magnet coils are of cotton-covered copper wire and are wound on frames or bobbins of thin sheet steel, *b b*, insulated with varnished paper, the bobbins being slipped over the cores after the wire has been wound.

The construction of the armature, which is well-designed and built with extreme care, is shown in fig. 181. H is a cast-iron hub, having three radial arms, W ; it is securely keyed on to the steel shaft, its length along the shaft being equal to the length of the finished core. The extremities of the arms are planed to fit into notches in the core plates, C, as shown in fig. 183, which is a section through the armature core and hub taken at right angles to the shaft. The core plates are of thin charcoal iron, and between them at equal intervals are placed three pairs of thicker rigid plates, which are kept a little distance apart by pieces of hard fibre, thus affording spaces for the circulation of air for ventilating purposes. The plates are separately well varnished and then built up, and while under high pressure between temporary end-plates, the core is slotted to receive the arms, W, of the hub. The lettering of figs. 181 and 183 corresponds. In the former, one arm, W, is shown directly below the shaft, while above it is the air-space, S, between the other two arms.

At one end of the shaft is provided a solid boss, K, and against this bears a cast-iron plate, P, in which are inlets, D D, for the passage of air. The core is held between P and a similar end-plate, R, which is secured by a steel nut, N, screwed on to the shaft. The ventilation is thus most efficient, for the air can enter through each end-plate by openings similar to D, and find its way along the spaces, S, between the hub and core plates, leaving by the openings between the rigid plates previously referred to.

FIG. 183.

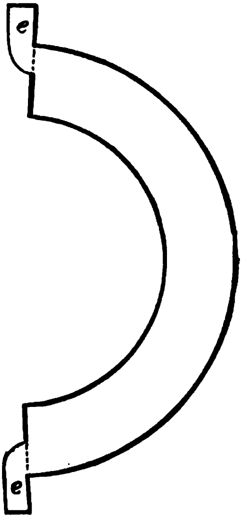


Before being wound the core is turned in a lathe to obtain a perfectly cylindrical and smooth surface. At intervals round the thicker plates there are projections, which serve to drive the conductor and prevent its being stripped. These projections are shown on the middle pair of plates in fig. 181, and, in addition to these horns, the completed armature is bound round in several places with thin strong wire which effectually overcomes any tendency towards bulging or stripping.

There are 204 active conductors round the periphery of the armature, each consisting of a straight strip or bar of copper 0·0215 sq. in. in sectional area, insulated with a double cotton covering. They project to different distances over the edge of the core, and are soldered to the ends of peculiarly shaped copper strips which form the cross connections.

One of these connecting strips is shown in fig. 184. It is a stamping of sheet copper and forms almost, but not quite, a semicircle, because it is required to extend round the end of the armature just far enough to connect two bars which are almost at opposite extremities of a diameter. The connector is placed with its plane parallel to the plane of the core discs, and the two small end-pieces or tags, *e e*, are bent round at the part shown by the dotted lines until they are at right angles to the other portion of the strip. The ends of the two conductors which are to be joined together are soldered to these pieces (*e e*). In fig. 181 the conductor A is connected to the tag *e*. Each section of the armature consists of two convolutions, that is, four active conductors, and the cross-connectors occupy a comparatively small space, a section through the whole of them being shown at L L. Over the shoulder of each end-plate is fixed a cast-iron ring, T, with a wide deep groove in which the connectors are placed, each well insulated by being over-wound with tape treated with shellac varnish. There are fifty-one bars in the commutator, and the method of holding them in position is shown in the longitudinal section. They have two square notches, into which fit rings of hard vulcanised fibre, the sections through which are shown black in the figure, and it will be observed that there is a deep groove on the outer side of each ring. A gun-metal sleeve is keyed on to the shaft, one end fitting into the groove of one insulating ring, while a thread is cut round the other end for a nut, which, when screwed up home, presses a gun-metal ring into the groove of the other fibre ring. The commutator bars are insulated from each other by mica, and each brush is divided into two independently adjustable parts, this being a better arrangement than one wide brush, which would probably wear unevenly and, in consequence, cause a considerable variation in the amount of surface contact. The sectional view also shows the manner in which the rocking bar is carried round a groove at the end of the cast-iron standard, and the fixing of the horizontal brush spindles, which are insulated from the rocking bar by hard wood collars. Various other mechanical details are set forth in the drawings, but perhaps it should be mentioned that the radial lines round the outer edge of the armature in fig. 182 indicate the edges of the small pieces, *e e*, of the connectors.

FIG. 184.



This machine is shunt-wound, and, when driven at 680 revolutions per minute, develops an E.M.F. of 120 volts, its maximum output being 12,000 watts. The resistance of the armature when cold is 0·045 ohm and of the shunt coils 40·9 ohms.

The sectional area of the iron in the armature core is 58 sq. in., and the maximum magnetic induction through it is 20 Kapp lines, while the sectional area of each limb of the field-magnet is 67·5 sq. in. and the magnetic induction through them 12 Kapp lines.

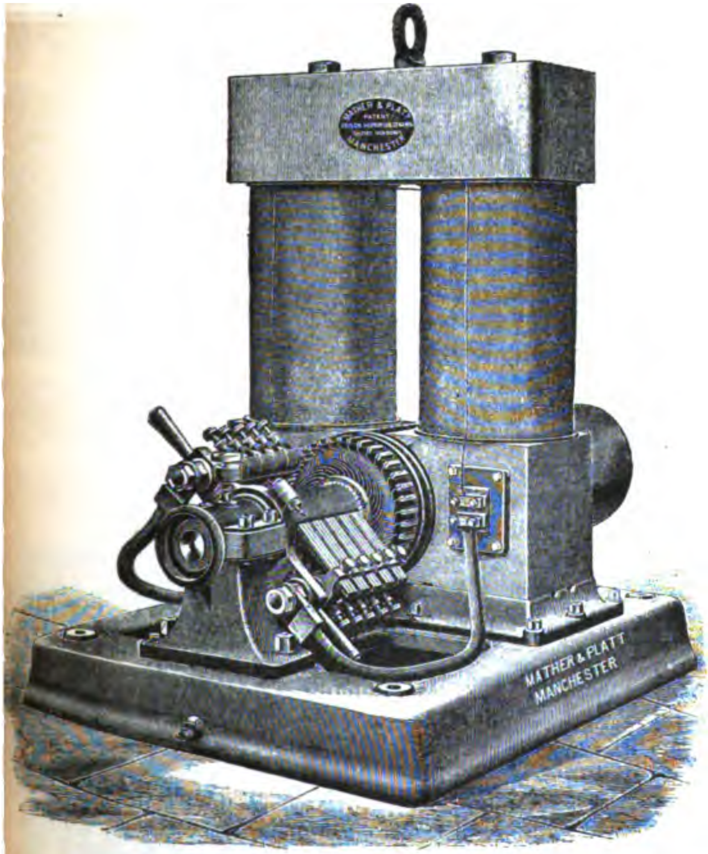
The unit of magnetic induction here referred to was introduced by Mr. Kapp, who considered it more suitable for practical purposes than that based on the C.G.S. system. One Kapp line is equal to 6,000 C.G.S. lines, and the unit of area is taken as the square inch instead of the square centimetre. This departure is perhaps, in some respects, unfortunate; but the method will probably survive, as it is already used by the majority of English manufacturers. The conversion from one system to the other can, of course, be accomplished without much labour, remembering that one square inch contains about 6·45 square centimetres.

Therefore the magnetic induction through the armature core above referred to is about 18,600, and that through the field-magnet 11,100 C.G.S. units.

Many forms of dynamo machines have been introduced Mr. Edison. In some of the earlier ones the field-magnets consisted of a number of straight electro-magnets of circular section divided into two sets, terminating in a pair of massive pole-pieces between which the armature revolved. This form of construction was essentially bad, on account of the large amount of wi quired as compared with the mass of iron in the cores, most economical form in this respect is a single circular co

Since the laws which govern dynamo construction have be better understood, Edison's field-magnets have, of course, provided with single massive cores; but in England the gre provement made on the machine was due to Dr. Hopkinson, in fig. 185 is illustrated the latest form of the 'Edison-Hopki dynamo. It differs from the machines already described in the armature is placed at the lower ends of the field-magnet co an arrangement which at one time was frequently employed. which has the disadvantage that the iron bed-plate more or gnetically short-circuits the pole-pieces, and affords a path rough which some of the lines of force leak, instead of passing rough the armature. On the other hand, there is the advantage at the centre of gravity of the moving parts is kept low, thus

Fig. 185.



adding to the stability of the machine, and also in some cases affording facilities for driving direct from a steam-engine fixed upon the same bed-plate. In the machine under notice this leakage is reduced by interposing a massive slab of zinc between the p pieces and bed-plate, as in fig. 185. We will endeavour prese to see to what extent this is successful.

Each of the circular field-magnet cores, together with its p piece, is a single forging of wrought-iron; the yoke is als wrought-iron, rectangular in shape and very massive; it is secu to the cores by two bolts, and great care is taken to make the s faces in contact fit truly, so as to avoid, as far as possible, t introduction of any magnetic resistance. The armature bearings are carried by short cast-iron standards bolted on to t bed-plate. The armature is drum-wound, and its core is buil of thin discs, insulated with paper, and threaded on to the shaft. Two thick stiff end-plates hold the core-discs in posi one bearing against a washer which is shrunk on to the sh while the other is driven up tight by a large nut. There are f sections in the armature, each of one convolution, and the c ductor consists of thick copper bars, the cross-connections be made with stiff copper strips. These strips, the outer set of can be seen in the figure, are led round spirally to the seg of the 40-bar commutator in such a manner that a coil plane is vertical is connected to segments which lie near the h zontal, and, consequently, the diameter on which the brushes set is nearly parallel, instead of at right angles, to the direc the lines of force through the armature.

The machine illustrated is shunt-wound, the wire compo the field-magnet coils being rectangular in section, thus red the waste space between the adjacent convolutions. The term of the machine are fixed on the pole-cheeks, and the marked ference in the size of the massive conductor which carries whole current from the brush-bar to the terminal, compared the thinner shunt wire, will be observed. When driven at revolutions per minute, this machine is capable of devel 52,500 watts (105 volts, 500 amperes), and on account of the tremely low resistance of the armature, it is practically self- lating through a considerable range. Each brush is divided five sections, all adjustable independently, and by this mea sufficiently large bearing surface upon the commutator is obt without introducing any difficulty in compensating for wear, such as would arise if one undivided brush were emp

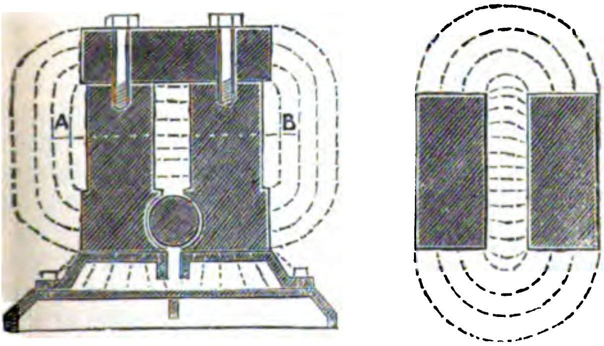
This type of dynamo is additionally interesting from the fact t it has been carefully studied and tested by the Drs. Hopkin- ı, the results having been published in various papers. The ect was (*a*) to endeavour to gain such information as would ble the performance of a dynamo to be predicted, when its figuration and the various dimensions and qualities of the erial employed (especially the iron) are known ; and therefore to enable any machine desired to give certain results at a ain speed, to be designed with the greatest accuracy.

We know that in every machine the magnetising force required develop the field in which the armature rotates is always in ess of that usefully employed ; or, in other words, more lines of e are generated than actually pass through the armature core, difference being caused by leakage at various points.

We will briefly describe one portion of the experiments with view of enabling the student to better judge of the amount locality of such leakage in any given machine.

The portion of the experiments referred to consisted in the place of determining exactly the ratio of lines of force actually rated, to the lines passing through the armature core. This will of course always be greater than unity, and may be ted by *v*.

FIG. 186.



n fig. 186, a machine with rectangular cores is shown in on, and lines of force are sketched to roughly indicate the principal paths of the leakage. Some of the lines pass direc from one limb to the other, others leak out of the yoke to th pole-pieces, while many pass through the arched slabs of (on which the pole-pieces rest), down into the iron bed-plate.

We have previously mentioned that it is possible to comp the number of lines of force cutting or cut by a coil of wire two or more given fields, by placing a galvanometer in circ with the coil and observing the deflections. As the result E.M.F. is usually comparatively low, the galvanometer must a delicate one, and it is usual to employ one in which a sm strongly magnetised needle is suspended by a silk fibre inside coil of many turns, the deflections of the needle being made dent by the movement of a beam of light reflected on to a sc by a small mirror fixed to the magnet. But in such a test it necessary that the needle shall not begin to move or change position until the whole of the brief current has actually pa through the coil, and it is preferable to make the needle s and somewhat heavy, avoiding as far as possible the introduc of any damping effect. The number of divisions on the scale velled over by the beam of light may then be taken as proport to the E.M.F. developed, and therefore to the number of of force cut.

In the experiments under notice a current of 5·6 amperes maintained through the field-magnet coils, from a battery, armature being disconnected. A single convolution of wire then wound round the middle of one limb as at B, the ends of wire being joined to an instrument such as that just referred and known as a ballistic galvanometer. The needle being at the field-magnet coils were short-circuited, thus suddenly ping the current in them, and the lines of force, in collapsing, the single turn of wire and induced a current therein, passing through the galvanometer, deflected the beam of light a moment. The needle having again settled itself steadily at the short-circuiting connection was removed, thus once suddenly passing the current through the magnet coils. The of force in springing outwards again cut the single coil, induc current which deflected the needle to an almost equal extent in the opposite direction to that produced by the first current.

s case the mean of the two deflections was 264 divisions, which, lecting the small amount of residual magnetism, may be taken proportional to the induction in, or the number of lines of force sing through, the field-magnet limb. The next step was to ermine what proportion of these lines passed through the ature, which was of the drum type, each coil consisting of one volution only.

The wires leading from the galvanometer were soldered one to of two adjacent commutator bars, and the armature placed so the plane of the coil connected to those bars lay at right angles e lines of force.

The field-magnets were excited as before by a current of mperes, and the deflection noticed first when the current in was stopped by short-circuiting, and again when the current sent round them a second time, so as to suddenly withdraw lines rce from, and then to thrust them through the armature core. mean of these two deflections was 200 divisions, and therefore

$$\frac{\text{Induction through field-magnets}}{\text{Induction through armature}} = \frac{264}{200} = 1{\cdot}32 = \nu.$$

is to say, 24·24 per cent. of the total number of lines of generated failed to reach the armature core owing to leakage. ough this method does not give us the actual number of lines rce in C.G.S. units, it nevertheless gives the proportion cor-y, and in these experiments the number passing through the ture was estimated in C.G.S. units by running the machine known speed and measuring the resulting E.M.F. without ing a current to pass through the armature and distort the Then the actual number of lines in any other part of the etic circuit could be found by simple proportion. Having n that 24·24 per cent. of the lines of force were lost by ge, the next step was to localise that leakage, that is, to ver at what points it occurred. This time the galvanometer, less sensitively adjusted, gave a mean deflection of 115 ons with one turn round the middle of one limb, when a nt of 5·6 amperes through the field-magnets was suddenly d and stopped as before. Four convolutions were then d round the bed-plate directly under the armature shaft, and, the current being stopped and started in the field-magnets, the galvanometer indicated a mean deflection of 50·25 divisions, due to the lines of force which leaked through the bed-plate and on the four convolutions wound round it. Four turns were employed in order to get a fairly high deflection. The induced E.M.F. being, however, four times that which would be obtained with one turn, it becomes necessary, to enable this result to be compared with the previous one, to reduce it to the value of one convolution, thus :

$$\frac{50·25}{4} = 12·6 \text{ divisions, nearly.}$$

The leakage through the space between the field-magnet li was measured with a coil of ten turns wound on a square fra and by a similar calculation was found to be proportional to divisions with one convolution.

The horns of the opposite pole-pieces approach each both above and below the armature to within 12·7 centim the depth of each being 8 centimetres. The leakage across of these gaps was found to be 1·6 divisions, or 3·2 divisio the two. Reducing these losses to percentages of the induction, we have

The leakage through the zinc plate and iron base	= 10·3	per ce
The gaps between the horns account for	2·8	"
And the area between the limbs . .	7·0	"
Making a total loss accounted for .	20·1	"
Out of an observed loss of . . .	24·24	"

The leakage through the shaft and from pole-piece to yoke, one pole-piece to the other by exterior lines will account remainder.

This ratio, *v*, will, of course, vary slightly with differen citing currents in the field-magnet coils, especially when the approaches the saturation point, because, the permeability iron decreasing with the induction through it, while that of remains constant, the proportion of leakage will be greater.

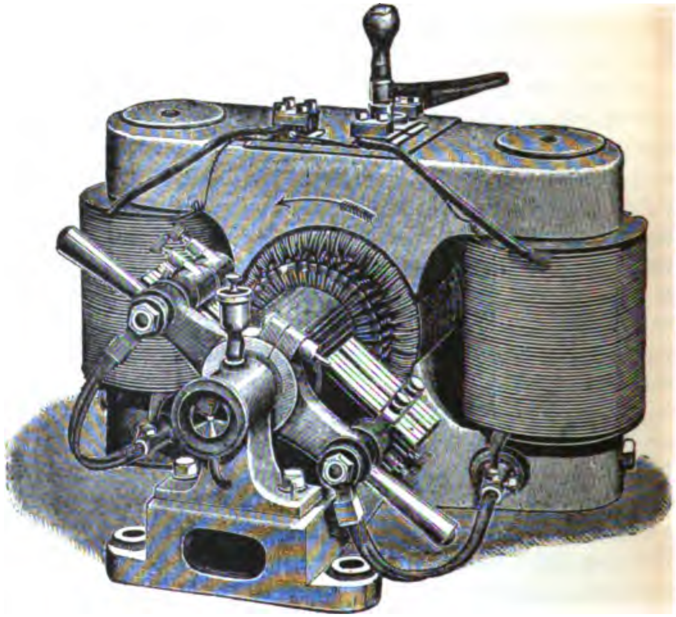
These experiments constituted the first definite atte discover the extent and the locality of the leakage of lines of generated by the current in the field-magnet coils, and it will be seen that almost a quarter of the power spent for the purpose of developing the field in this particular case was wasted. The large proportion of the leakage for which the bed-plate accounts shows the great advantage pertaining to the inverted horse-shoe form of field-magnet. It is to be regretted that the other types of field-magnet which are now extensively employed have not been subjected to similar experimental examination, but a study of these experiments, together with those made in connection with the machine next to be described, should enable the student to make a very fair estimation in any ordinary case.

It would, for instance, be safe to predict that for a given magnetic saturation of the iron, comparatively little magnetic leakage would take place with the machine depicted in fig. 175, for the brackets are made of gun-metal, and, excepting the shaft, there is practically no magnetic metal employed which would tend to increase the leakage. In this respect this machine is probably the best of any we are acquainted with; but we may again remark that the amount of leakage also depends largely upon the degree of saturation of the iron, and upon the magnetic resistance of the whole magnetic circuit. On the other hand, it would be false economy to make the leakage extremely low, if the extra expense incurred in so doing were out of proportion to the cost of the power which would otherwise be wasted in the generation of the field.

The 'Manchester' dynamo, made by Messrs. Mather & Platt, is illustrated in fig. 187. The arrangement of the field-magnets differs somewhat from that in the machines hitherto described. Two electro-magnets are fixed vertically with their like poles uppermost, the similar poles being in each case joined together by massive iron yokes, shaped as shown, so as to form the pole-pieces between which the armature rotates. The lines of force due to the field-magnet coils are thereby provided with an easy path for completing their respective circuits, and an intense field is projected through the armature. The vertical members of the field-magnets are of wrought-iron, let into the horizontal yokes, which, being of cast-iron, have about twice the sectional area of the cores. The lower casting is extended on both sides so as to form the bed-plate of the machine, and the centre of gravity of the moving parts being low, it is comparatively easy to rigidly fix the machine in order to obtain great steadiness in running.

The shaft carrying the armature is made of Bessemer steel, the bearings being of gun-metal, and a free space along the shaft is provided to admit air for ventilating the armature. When driven at 1,100 revolutions per minute, the machine illustrated, which is compound-wound to maintain a potential difference of 100 volts, is capable of generating a current of 80 amperes or a maximum output of 8,000 watts.

FIG. 187.



The commutator in all dynamos of this type consists of forty bars of hard-drawn copper insulated with mica. Each arm of the rocking-bar carries two brushes, each brush being independently adjustable for the reasons already explained. The diameter of commutation with machines of this class, in which the direction of the lines of force through the armature is vertical, approximates to the horizontal, and this position in the Manchester machine is more nearly approached in consequence of a peculiarity in the curvature of the pole-pieces. Instead of the polar surfaces being made concentric with the armature, they are struck from a radius greater than that from the centre of the shaft, so that the pole-pieces are brought slightly nearer the armature at points opposite the extremities of its vertical diameter. The lines of force are therefore more concentrated at these places, which reduces the distortion, and, increasing the activity of the most active or vertical coils, decreases that of those near the neutral point.

The armature is of the ring type, the core consisting of the usual thin iron discs clamped between the ends of a gun-metal frame. The arms of this frame, which fit into slots in the discs, are free of the shaft, so that a clear space for ventilation is retained. The end-plate nearest the commutator is keyed to the shaft, while the other is held up tight against the plates by means of a nut. The wire is wound in forty pairs of coils, the resistance from brush to brush being 0·084 ohm.

The shunt coils on the field-magnet have a resistance of 41·5 ohms, and the series coils, which are wound outside the shunt coils, have a resistance of 0·049 ohm.

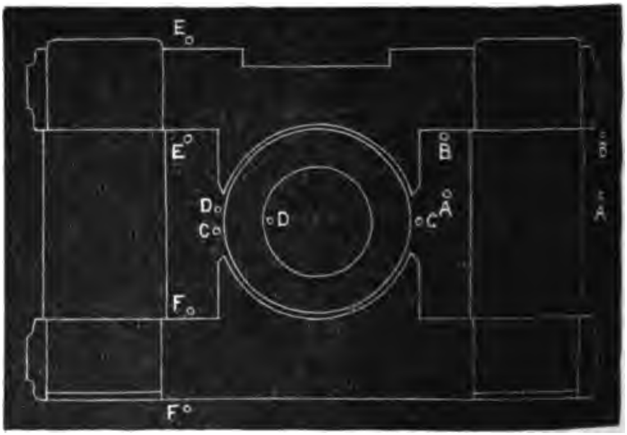
The gross weight of the machine is 10¾ cwt.

The brothers Hopkinson also made on this machine some experiments similar to those already described, and we may briefly refer to the simpler of the experiments which show the percentage and the locality of the leakage of the lines of force. Fig. 188 gives an outline of the machine, and shows the various positions of the testing-coils. As in the other experiments, the armature was disconnected, and a constant current obtained from an independent source to magnetise the field-magnets, the lines of force being made to cut the testing-coil by suddenly starting and stopping the current in the field-magnets, and the mean of the two observed deflections of the ballistic galvanometer calculated as before. In the first experiment four turns were taken round the middle of one limb at A A, and the mean deflection was observed to be 214 divisions. But as with a single turn of wire only one-fourth of this would have been obtained, $\frac{214}{4} = 53·5$ represents the total induction through the field-magnet core in terms of the arbitrary unit here assumed. But an equal number of lines pass through the other vertical limb ; therefore, the total induction through the field-magnet cores, as shown by this first measurement, may be represented by 107.

The coil was then raised to B B, where the mean deflection was 206, or, for a single turn, $\frac{206}{4} = 51{\cdot}5$, or 103 for the *two* limbs, and the mean of these two results—viz. 105—was taken as the mean induction in the field-magnet cores.

Three turns were wound round the armature at C C, where the deflection obtained was 222 divisions, or, for one turn only,

FIG. 188.



$\frac{222}{3} = 74$, which represents the total induction through the space occupied by the armature. But we know that in a Gramme ring a certain number of lines pass diametrically across instead of round the armature core, which number becomes greater when the iron is so saturated that its permeability is low—perhaps lower even than that of the shaft—and the next experiment sought to determine the waste due to this cause. Four turns were taken round D D, the deflection being 141, or 35·25 in terms of one convolution. But as an equal number of lines pass through the other half of the ring, we must double this, getting 70·5 as the effective induction through the core, against 74 through the whole armature space and 105 through the field-magnets.

At E E 39·75 divisions due to one convolution were obtained, and, the induction being the same on the other side, the total induction = 79·5.

At F F the result was higher, being 41·75, or 83·5 for both sides, the difference being caused by the easier path at the bottom of the machine offered by the bed-plate and bearings, and, of course, these additional lines are wasted.

We see, therefore, that in this case a large number of the lines of force generated are wasted; in fact, here

$$\nu = \frac{\text{lines through field-magnets}}{\text{lines through armature core}} = \frac{105}{70{\cdot}5} = 1{\cdot}49 \text{ nearly.}$$

This loss is partly accounted for by the extension of the lower yoke-piece to form the bed-plate and the use of iron supports for the bearings, and is, no doubt, fully compensated for by advantages from a mechanical point of view. But it will be observed that almost 5 per cent. of the lines passing through the armature leave the core and pass diametrically across the ring; this large proportion is, in a great measure, due to the fact that induction through the armature core was very high, viz. 20,000 C.G.S. units.

Another form of double horse-shoe magnet machine, and one which differs considerably from any yet described in several important mechanical and electrical details, is that constructed by Messrs. Laurence, Paris, & Scott, and illustrated in fig. 189, a section through the machine being also shown in fig. 190. The field-magnets are of cast-iron, made in two parts firmly bolted together and provided with flanges to hold the four exciting coils, the lower casting having additional flanges to receive the foundation bolts. The armature shaft is supported by cast-iron brackets provided with gun-metal bushes and bolted to projections from the lower pole-piece. The pole-pieces are bored out circular to form the armature space. The armature is drum wound, but is furnished with teeth projecting between each of the sections, one of the earliest forms of armature devised by Pacinotti, these projections are known as Pacinotti teeth.

The chief objection to this type of armature core is,

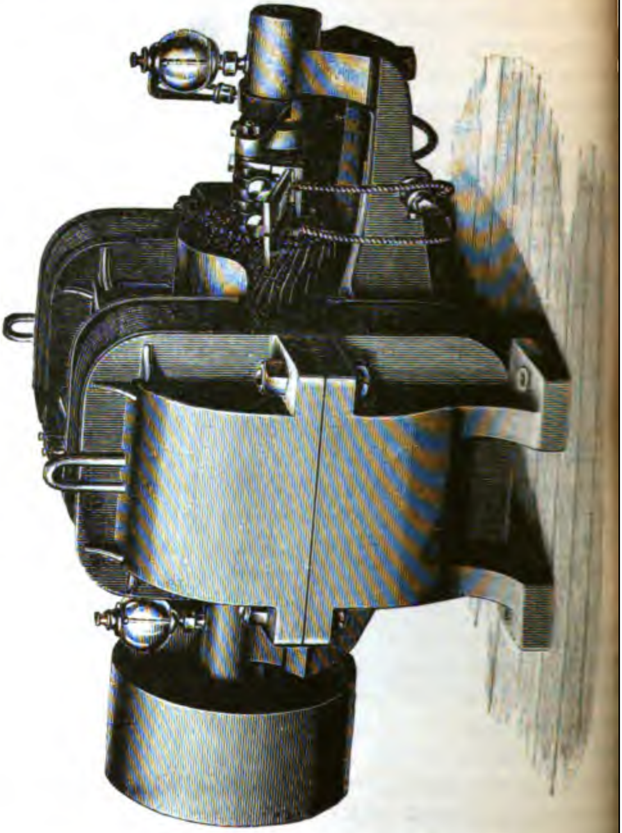


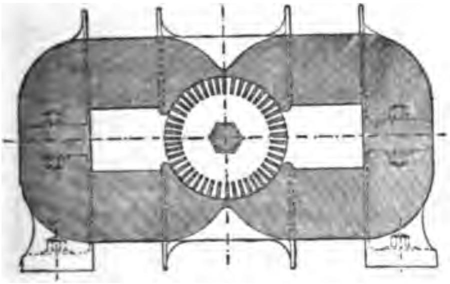
FIG. 18

although some of the iron is brought nearer the field-magnet its uneven surface perturbs the magnetic field, keeping it in a of oscillation, and setting up eddy currents in the field- poles. But in the machine under notice this effect is

:ely obviated by employing a large number of teeth and making distance between them very small, so that the oscillation of the is very slight—indeed, practically imperceptible. One section ıe armature is wound in each slot, which is just wide enough ıke a single insulated wire, and deep enough to hold the ber of wires in each section.

n the armature shown in fig. 190 each section consists of six olutions, so that there are six wires in each slot. If the slots made too deep, some of the lines of force would not be cut ıe inner wires; in the present case, the number thus missed y small, practically none being lost in armatures having but ɪurns in each section. The core is built up of thin discs ft iron, of the shape shown in the sectional figure. The

FIG. 190.



: holes are hexagonal, and the plates or discs are threaded the hexagonal steel shaft, so that each one is driven direct it. This, added to the fact already mentioned, that the wire ınd in deep and narrow slots, makes the armature as a whole anically strong, there being little risk of a sudden stress ıg the core or stripping the conductor from its place. There unusually large proportion of iron in the core; in fact, the of the space, except the small amount taken up by the insulating material, is occupied by the iron plates and steel shaft, no ınce whatever being made for ventilation. It will be observed, ʼer, that a large amount of the iron core (the edges of the ı is in direct contact with the air, and as the armature rotates the heat is carried off by convection, thus preventing any gr rise in temperature. The facility afforded in this way for th dissipation of the heat generated in the core, gives to th Pacinotti ring one very important advantage. The commutator sections or bars are insulated with mica, rings of asbestos a fibre being employed at the ends of the bars to insulate the from the clamping-nut and washer by which they are held position.

When the machine is compound wound, the series turns a usually wound on the top magnet cores. Should the series c not occupy the whole of the wire-space, it is filled up with a portion of the shunt wire, which also occupies the whole of the spa on the lower magnet cores.

For large machines, sheet copper, insulated with strips of calico is used for the series winding.

The following details concerning one of these machines, ver recently constructed to give 12,000 watts at an E.M.F. of 100 vol when driven at 710 revolutions, will be of service.

The armature is wound in fifty-two sections, each of two co volutions, so that there are fifty-two bars in the commutator a two wires in each slot. The sectional area of the cast-iron fi magnet cores is considerably greater than that of the arm core, the former being 98 and the latter 29·7 square inches. maximum magnetic induction through the armature core is 23 Kapp lines per square inch, or about 21,000 C.G.S. lin square centimetre.

The armature conductor is of braided wire, very c insulated from the core and from the adjacent wire in th slot, and the current density in the conductor, with 120 a is 3,210 amperes per square inch.

The series winding on each of the top limbs consists of t eight turns of sheet copper, 4·5 inches wide and 0·025 inch having a resistance of 0·0124ω, and giving, with the ma current, 3,360 ampere turns.

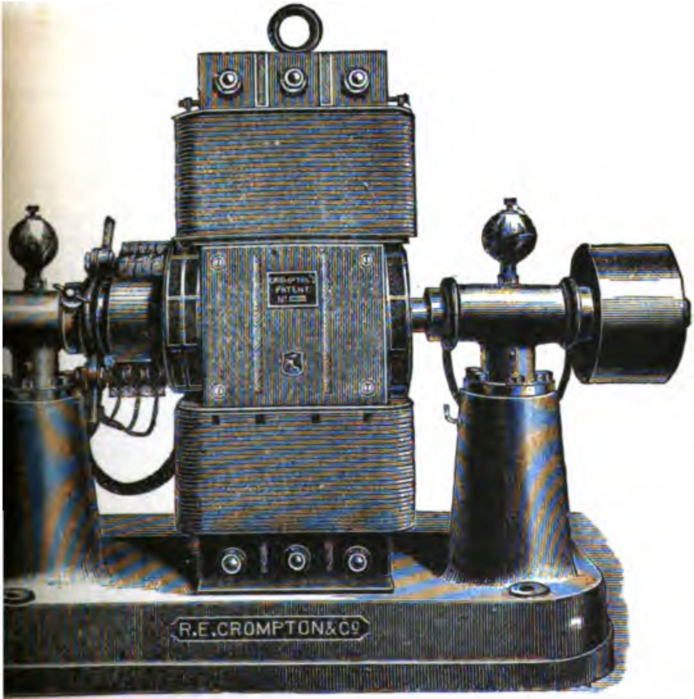
The resistance of the shunt coils is 32·4ω, the ampere-t with the potential difference of 100 volts, being 6,468.

We may from the above easily determine the number of w expended in the various parts of the circuit, remembering th ount developed in the external circuit when the maximum rent is being obtained will be E C = 100 × 120 = 12,000 ts. Thus,

Shunt coils 32·4$^{\omega}$, watts lost with 100 volts = 308
Series „ 0·0124$^{\omega}$, „ „ 120 amperes = 178
Armature „ 0·045$^{\omega}$, „ „ 120 „ = 648

Fig. 191 illustrates the 'Trade' dynamo of Messrs. Crompton 'o. It is somewhat similar to the Manchester dynamo, and to

FIG. 191.



just described, in that it consists of a double electro-magnet, lifference being that it is fixed vertically instead of horizontally. field-magnet cores are of annealed wrought-iron, and are fixed by bolts and nuts to the cast iron bed-plates. The coils are wound on four bobbins, and connected in such a manner that the two coils on the same magnet limb have their similar poles adjacent, the pair on the one side having their north poles and the on the other side their south poles adjacent, so that the lines of force pass horizontally through the armature from and into those portions of the vertical limbs between the coils, which portions therefore form the pole-pieces.

This machine is furnished with a ring armature, in which the iron discs are insulated by varnished paper, the built-up core being dried in an oven before the conductor is wound over it. The steel shaft has four longitudinal grooves, into which fit radial bars of aluminium bronze, their length along the shaft being equal to the length of the core. The outer ends of these bars dovetail into notches in the discs. The conductor is of rectangular cotton-covered wire, wound in one layer on the outer circumference, but in two layers over the inner face of the core, which, besides being smaller, is partly occupied by the radial driving bars. Insulated steel wedges project at intervals from the core, to drive the conductor on the outer circumference, and the armature is also bound over with thin tinned steel wire to prevent bulging. The brushes are of stencil copper, carried on a gun-metal spindle which is insulated by a fibre collar from the cast-iron rocking-bar.

We have remarked that it is not possible in practice to 'compound' a machine to give a constant current, in the same manner that a constant potential can be maintained. Hence a variety of other devices, mostly mechanical, have been suggested for the purpose, one of which has already been described, and we will now direct attention to a machine designed and constructed by Mr. J. G. Statter, to maintain a constant current at a constant speed when the external resistance is varied; or when the speed is varied and the resistance remains unaltered; or within certain limits when both speed and resistance vary.

When an armature is rotated in a simple field, with the brushes removed from the commutator, there are two points, at opposite extremities of a diameter, at one of which the potential is a maximum (positive), and at the other a minimum (negative), and it is at these points that the brushes should be set in order to in the greatest difference of potential. From the negative to positive brush either way round the commutator, the potential lually increases in value, and if the negative brush were shifted, 20° forward, it would touch at a point of higher potential, and sequently the *difference* between the two brushes would be re- d. A like reduction would follow if the positive brush were ed forward, because it would then make contact at a point of r potential; and in the third case the difference of potential een the two might be decreased by giving them simultaneously eater angle of lead, until they would be at nearly the same ntial when moved through an angle of 90°.

t follows that by merely shifting the brushes the potential rence at the terminals may be made what we please from the mum downwards, and this method might be employed to vary ressure, and therefore the current, to suit the requirements of ircuit. Thus the brushes might be set 20° ahead of their normal ion of no sparking—that is, where the difference of potential een them is at a maximum—and then, if the current became trong, the brushes could be shifted yet further ahead, thus re- g the potential difference and also the current; while by mov- e brushes back towards their normal position, the current could creased in strength, should it fall below the desired value.

his would, however, be impracticable in an ordinary dynamo, count of the terrific sparking which would ensue; and one of rincipal features in Mr. Statter's machine is the method by he renders it possible to vary the lead of the brushes through siderable angle, without causing this sparking.

onfining our attention at present to the case of ring arma- , it will be remembered that when a coil which is carrying the of the current generated in one half of the armature is -circuited by the brush, the electro-magnetic inertia of the due to its self-induction, prevents the instantaneous cessation e current; and that even if the coil is commutated at the ent when its plane is exactly at right angles to the field and fore in itself inactive, yet there will be a considerable spark d by what we may term the self-induction current in the coil. this reason it is found to be necessary to give the brushes a extra lead so that the coil may begin to cut lines of force, and have induced in it an opposing E.M.F. sufficiently stro just counteract this self-induction effect, and stop the curre the coil before the brush leaves its commutator bars. Now th weaker the field the greater is the extra lead required to ob this opposing E.M.F. The extra lead also increases with the s induction of each individual coil, while in the case of some a tures, having but one or two convolutions in each section, practically *nil*.

It must be remembered that this *extra* lead is not due to distortion of the field, but is simply required to prevent the sp which would otherwise result from the self-induction of the c Neither must it be forgotten that if the current is kept cons in strength, the E.M.F. thus required to be counterbalanced is same whether the coil is short-circuited at 10°, 20°, or ahead of the normal position. In an ordinary field the actio the coil increases with such rapidity as it leaves the n position, that the self-inductive effect is more than balanced there is a remaining E.M.F. opposite in direction induced b field on the coil, which is then competent to cause sparking.

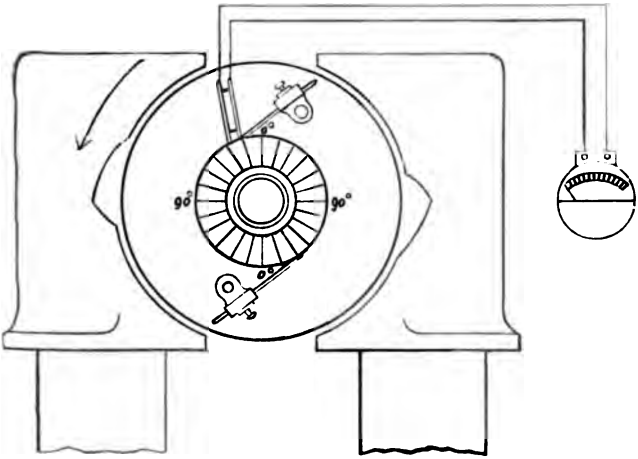
But if the field were made uniform and of such strength for a certain distance beyond the neutral point—say throug angle of 40°—the number of lines cut by the coil at any pos in that angular space was just sufficient to counterbalance E.M.F. of self-induction, then the potential difference at the en the coil throughout that range would be *nil*, and no spar would ensue if it were short-circuited.

This is Mr. Statter's method; and in order to allow a st field to be employed, each coil contains an unusually large n ber of convolutions, there being also plenty of iron in the arm so that a strong field is required to counterbalance the res high self-inductive effect. Portions of the pole-pieces are away at such points as will make the density of the lines of entering the armature over a given angle equal; and the places where the field has to be increased or reduced in stre are ascertained by experimenting in the following manner.

A series machine is constructed in the ordinary way, b pole-faces concentric with the armature, but with a rather number of convolutions than usual in each armature section.

peed at which it is driven is kept constant, and also the current, ay at 10 amperes, when the effect of self-induction, which has to e balanced, but not over-balanced, will be constant also. The irst step is to find out what is the activity of a single coil at the arious stages of its circular path, and, in order to decide this, use s made of a set of apparatus which has been employed for different objects by other experimenters with good results. It consists of a voltmeter of the requisite range, having its terminals ttached by flexible wires to two copper strips, which are fixed at sufficient distance apart by pieces of insulating material, so that their ends bridge over the width of a commutator segment. The arrangement of this simple apparatus and the method of using it are indicated in fig. 192. While the machine is running, and sending a current through an external resistance, the exploring brushes, as we may term them, are held against the commutator, as indicated in the figure, and each coil as it passes the point where the brushes are placed is connected up for a moment to the voltmeter, which indicates the electromotive force developed in the coils while passing that position. The exploring brushes are shifted by suitable stages round the whole of the commutator, and

Fig. 192.



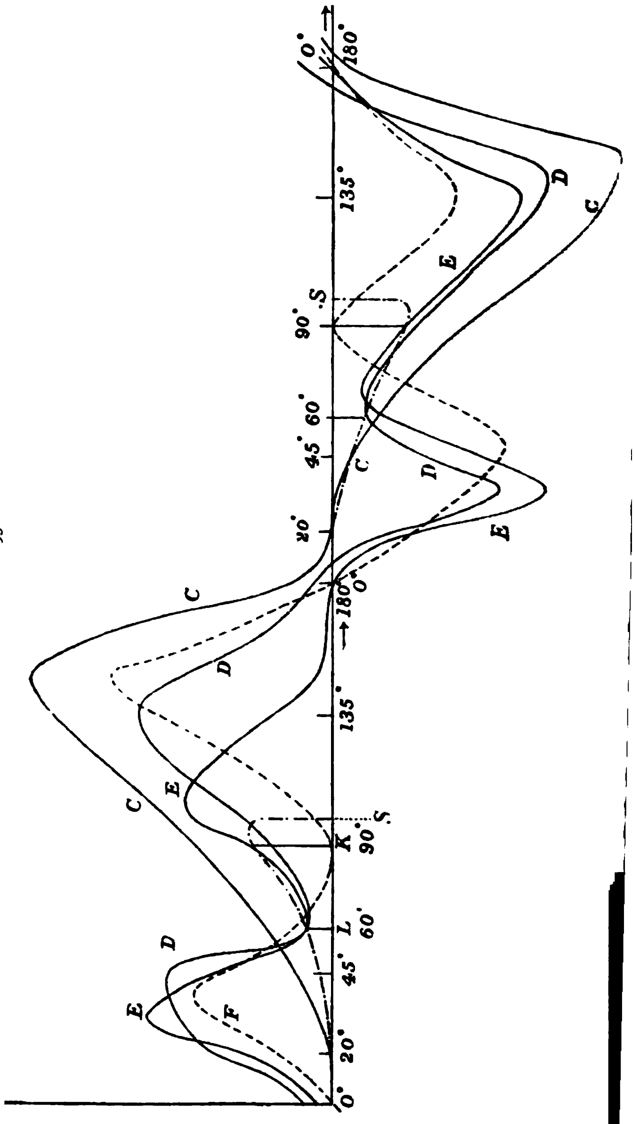


FIG. 193.

e deflection of the voltmeter noted for each position. The esults are plotted in the form of a curve (see fig. 193), the distances along the horizontal line being taken to represent the ngular distance of the coil from the zero position on the commuator, while the vertical distances represent the E.M.F. in volts leveloped by one coil in the various positions.

The curve C C was obtained in this manner when the main rushes were placed in the normal position, the lead being about 20°. The results obtained in passing *down* the commutator in the direction of rotation are plotted above, while those obtained in passing *up* are plotted below the line; and it will be observed that the E.M.F. at the extremities of each coil becomes *nil* at 20° from zero, while it is a maximum at about 150° from zero.

To facilitate comparison, both the point vertically above and that vertically below the centre of the shaft are regarded as zero points.

This curve having been obtained, the brushes were shifted forward to a position 60° from zero, and, regardless of sparking, the potential difference at the extremities of a coil in all the various positions was again measured. Another curve, D D D, was obtained by plotting these results, and it will be observed that, at the moment a coil is passing under the main brushes, the potential difference at its ends is considerable. This potential difference, which gives rise to the sparking, is in fact proportional to the height of the ordinate L, and it is equal to the excess of the E.M.F. induced in the coil by the powerful field at this point over that momentary E.M.F. due to the self-induction of the coil at the moment it is short-circuited. It is clear, then, that to eliminate the sparking when the main brushes are given a forward lead of 60°, the strength of the field must be reduced by just so many lines of force as would develop an E.M.F. proportional to the ordinate L, and then the E.M.F. of self-induction and that being induced in the coil would exactly balance. The length and number of active conductors in each coil, and also the speed of rotation being known, this number of lines of force can readily be determined.

The main brushes were next given a lead of 90°, when, as might be expected, the sparking became even more severe, but by means of the exploring brushes and voltmeter the curve E E E was rapidly obtained. The E.M.F. in excess, which at this position of the brushes causes the sparking, is represented by the ordinate L which gives a means of estimating the extent to which it is here necessary to reduce the strength of the field. About ten such curves were obtained with the brushes in various positions between 20° and 100°; but we have only given three of them in order to avoid a complex figure. From each point on the horizontal line corresponding to the angular distance of the main brushes from zero, a perpendicular is erected to cut the curve which was obtained with those brushes in that particular position (as we have observed, L and K are such ordinates), and by joining the tops of the whole of the ten ordinates the dotted curves starting at 20° and terminating at S are obtained.

The area contained between one of these curves and the horizontal line affords an indication of the amount of iron which should be removed from the corresponding pole-face in order to weaken the field to the desired extent.

But since the very act of increasing the distance between the pole-face and the armature core at one point increases the density of the lines of force at another adjacent point, the areas only approximately represent the shape of the cavity required in the pole-face. For this reason the curves are, in practice, simply used as a guide to indicate to what extent the field requires reduction at the various parts, and the iron is removed to a rather less extent than is sufficient, so as to allow a margin for any error. Other curves are then obtained by means of the exploring apparatus, and a second approximation to the final result is arrived at, the process being again repeated if necessary. The dotted curve F was obtained with the brushes at 90° after the pole-face had been shaped, and shows by its coincidence with the horizontal line at 90° that no sparking took place with the brushes in that position.

One method of modifying the field is to cut a groove in the pole-face parallel to the shaft, after the manner shown in fig. [illegible] and it will be seen that the outline of the groove approximates somewhat to the dotted shaping curves in fig. 193.

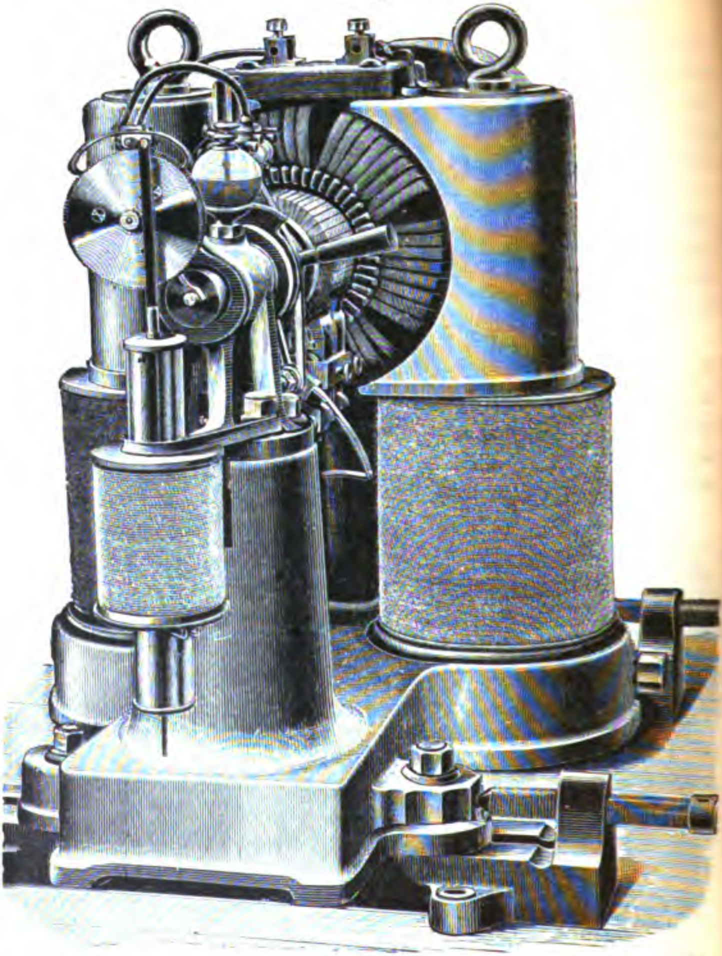
The desired result may, however, be obtained by removing the iron in a variety of ways, such as boring holes in the pole-pieces or even by using iron of different permeability.

We have here considered the case of a ring armature machine, n which the maximum number of lines which each coil can at ny one time embrace is only half the total number passing through he core. But in the case of a drum armature the whole of the ines can at once be embraced and cut by a coil during half a evolution ; it is therefore only necessary to 'explore' through 180° round the commutator, and plot the curves, say above the ine, to obtain one shaping curve. This will indicate approximately the amount by which the whole field must be reduced, and the whole of the iron may be removed from one pole-piece, or half from each, as in fig. 192.

In this manner, then, is it rendered possible for the brushes to be shifted through a considerable angle in order to vary the potential difference, and consequently the current strength, without introducing sparking. It now remains to show the method by which the brushes are automatically moved to the proper position when the current varies. A view of the machine, with its automatic regulator, is given in fig. 194. In this particular case, two deep grooves are cut in each pole-face, but they do not extend to the pole-cheek, so that, in external appearance, it is similar to an ordinary machine. The solenoid shown in the front of the figure is wound with thick wire, and is joined up in the main circuit, so that the whole current passes through it. Inside it is a core capable of a small vertical movement, its centre being below that of the solenoid. When the main current rises above its proper value, this core is sucked up, and throws into gear a simple mechanism which increases the lead of the brushes and so reduces the current ; similarly, a reduction in the current strength allows the core to fall, when the mechanism is reversed, and the brushes recede towards the zero or maximum potential position.

The bar which carries the brush-holders is placed, as usual, on the end of the bearing next the commutator, the collar, however, being adjusted and the bearing oiled so that the bar can rock easily. On the upper part of the collar is fixed a toothed segment, which gears with a pinion on a spindle parallel to the main shaft ; the other end of this spindle carries two ratchet-wheels, each 5½ inches in diameter, but with their teeth set in opposite directions. The nearer of these ratchet-wheels can be seen in the figure; the other is but $\frac{1}{8}$ inch behind it, and the two are rigidly fixed together by means of three set screws. When

FIG. 194.



these wheels are rotated, the pinion at the other end of the spindle on which they are fixed communicates the motion to the toothed

e have considered the case of a ring armature machine,
e maximum number of lines which each coil can at
e embrace is only half the total number passing through
le in the case of a drum armature the whole of the
t once be embraced and cut by a coil during half a
it is therefore only necessary to 'explore' through
the commutator, and plot the curves, say above the
in one sparking curve. This will indicate approxi-
mount by which the whole field must be reduced, and
of the iron may be removed from one pole-piece, or
ch, as in fig. 193.

manner, then, is it rendered possible for the brushes
d through a considerable angle in order to vary the
ence, and consequently the current strength, without
sparking. It now remains to show the method by
shes are automatically moved to the proper position
rrent varies. A view of the machine, with its auto-
ar, is given in fig. 194. In this particular case, two
are cut in each pole-face, but they do not extend to
h, so that, in external appearance, it is similar to an
ine. The solenoid shown in the front of the figure
thick wire, and is joined up in the main circuit, so
e current passes through it. Inside it is a core
small vertical movement, its centre being below that
d. When the main current rises above its proper
e is sucked up, and throws into gear a simple me-
h increases the lead of the brushes and so reduces
imilarly, a reduction in the current strength allows
, when the mechanism is reversed, and the brushes
s the zero or maximum potential position.

hich carries the brush-holders is placed, as usual,
the bearing next the commutator, the collar, how-
fitted and the bearing oiled so that the bar can
On the upper part of the collar is fixed a toothed
h gears with a pinion on a spindle parallel to the
the other end of this spindle carries two ratchet-
5¼ inches in diameter, but with their teeth set in
The action of these ratchet-wheels can be

---

nd so slightly alters the lead of
ward, according to the direction
ned.

iar, with a pawl at either end,
one being placed directly over
while the other gears with the
is running, the curved bar has
tion through a small angle, by
d a slot, in which plays a pin
he main shaft. In the normal
bar moves is such that neither
heel directly under it, but, by
the other, either pawl can be
wheel at every pulsation.

per direction by the movement
re being attached to the curved
when the current becomes too
wards, that pawl is thrown into
e brushes a forward movement,

igure, can be seen passing right
d to it, and, in fact, forms the
wire is wound. It is made of
h is a wrought-iron tube 1½ in.
enoid is 6 inches in length, and
entre being about 1 inch below
ay is limited to $\frac{3}{16}$ inch, so that
throw the pawls in gear.

kably well under the varying
the brushes steadily travelling
little sparking. The machine
to supply a constant current of
nps joined up in series, and is
ninute. Any alteration in the
e varies the external resistance,
es the brushes to compensate
mber of lamps joined up, the
als is 1,290 volts, so that the

power available in the external circuit is 12,900 watts. It is se wound, the resistances, measured when the wires were hot, be armature, 8·79 ohms; field-magnets, 3·3 ohms; regulating so noid, 0·57 ohm. There are sixty commutator bars, and number of convolutions in each section of the armature is fifty-f The magnetic induction through the armature is 17 Kapp lin or rather over 17,000 C.G.S. lines.

An interesting machine of this class is in use for genera the current for the Northfleet Tramway, where the motors on various cars are placed in series, and the power required rapidly and considerably, while the current must be kept cons at 50 amperes. The maximum E.M.F. at the terminals is 450 vo and the brushes are continually travelling backwards and forwa the sparking being hardly noticeable.

Another type of dynamo, manufactured by the same firm illustrated in section in fig. 195, the section being taken vertica through the spindle. The machine is designed to be driven dir by a steam-engine, which is built upon the same bed-plate wi and it is, consequently, calculated to develop the requisite E at a low speed.

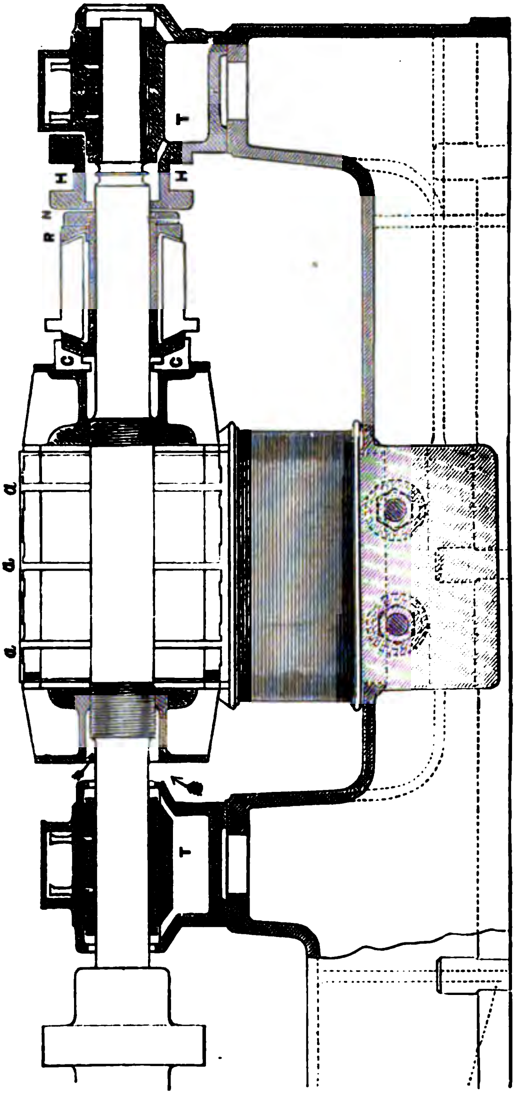
The framework is a hollow casting, well stayed with cross and cast solid at one part to form the yoke. The slabs form the limbs of the field-magnet are of wrought-iron, of the bra known as 'Kirkstall scrap,' carefully annealed, each finished weighing 8 cwt.; they are fixed on to the framework by two ho passing horizontally through the solid part of the casting.

The armature is drum wound, having Pacinotti teeth, the being made of thin discs of Swedish iron, punched out to required shape, and effectually insulated one from another by asbestos tissue and shellac varnish.

A number of keyways are planed in the shaft, and corresp ing horns or projections are stamped out on the inner edges the discs, to fit accurately into these keyways, the shaft be also fluted between them so as to afford air-passages under discs.

To form the Pacinotti teeth, the outer periphery of each is punched symmetrically with respect to the inner horns, so when the discs are threaded on to the shaft, rectangular groo

FIG. 195.

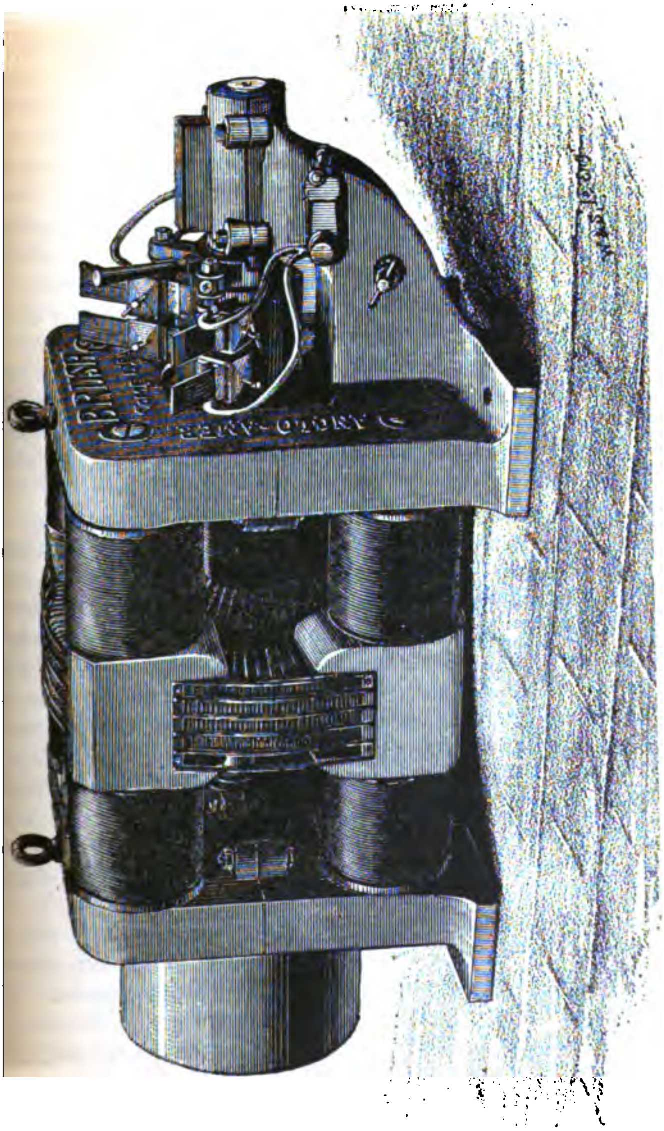


(with the greater dimension radial) are formed along the surface of the core, and in these grooves is placed the conductor.

The method of insulating the wire from the core is very effectual and somewhat unique. Strips of mica are placed in the grooves referred to, and cemented together so as to form a continuous trough. In addition to this the conductor is provided with a double covering of cotton, and a serving of silk at the angles where it is bent round the edges of the core. In threading the discs upon the spindle, three spaces, *a a a*, are left between them. Fan-blades are set in these spaces, and the whole of the plates are clamped together by the cast-iron end-plates, A and B, which are screwed upon the shaft. Underneath the plate A, at the end remote from the commutator, are little air-passages communicating with the flutings, previously referred to, in the shaft; and when the armature is rotated, air is drawn in as indicated by the arrows under the end-plate, and along the flutings under the edges of the discs, and is forced out at *a a a* by the fan-blades, thus giving most efficient ventilation.

Fan-blades, C C, are also fixed to the end-plate, B, nearest the commutator, at the back of which they maintain a current of air and prevent the accumulation there of dust or dirt. There are sixty bars in the commutator, each fitted with a lug, as shown, for connection with the armature conductor. The method of securing these bars is also clearly illustrated. Mica is employed not only for separating the bars from each other, but also for insulating them from the bush and cone ring by which they are secured. The bush, which is keyed on to the shaft, is of gun-metal, but in order to obtain a higher pressure the cone ring, R, and nut, S, are made of wrought-iron instead of gun-metal. The nut is cased with copper to prevent oil creeping down the threads, and inside each journal at T T, small tanks for waste oil are provided. The groove in which the collar of the brush rocking-bar turns is shown at H H. This particular machine develops a maximum current of 120 amperes at 100 volts, the speed being only 250 revolutions per minute. It is compound-wound, the resistance of the armature being 0·1 ohm, of the series windings 0·017 ohm, and of the shunt-coil 30 ohms.

A type of machine, differing from those previously considered,



in regard both to the armature and the field, is illustrated in fig. [illegible] It is known as the 'Victoria' dynamo, and is a development by Mr. W. M. Mordey of a machine originally designed by Schuckert. In the earlier days of practical dynamo-building, engineers were much exercised by the comparatively large proportion of wire [illegible] ring armatures which cuts few or none of the lines of force, [illegible] which, therefore, is called idle wire. The Schuckert machine [illegible] designed to minimise this as much as possible, by flattening [illegible] armature ring, and extending the pole-pieces so as to make [illegible] embrace more of the wire on the flattened sides of the coils. [illegible] arrangement did not, however, altogether answer the anticipations for by merely extending the pole-pieces, the density of the [illegible] of force was diminished, and, with a magnet developing a certain strength of field, it matters little whether that field is spread [illegible] and the lines of force cut by a long piece of wire, or whether [illegible] field is more concentrated and only cut by a portion of the [illegible] wire.

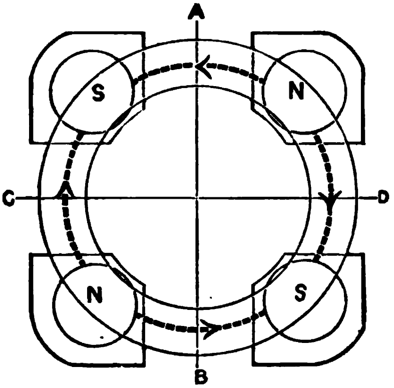
This form of armature, even when the best shape is given [illegible] the pole-pieces, is in reality slightly less efficient than either [illegible] ordinary ring or the drum form, but it is, nevertheless, a favourite chiefly because it offers good facilities for ventilation, is very [illegible] in construction, and (owing to the sectional shape of the armature coils) there is but little tendency for the wires to fly out [illegible] driven at a high speed. Flat ring armatures are also usually [illegible] to rotate in a 'multiple field,' that is to say, the field is generated by four, six, or sometimes eight poles.

Fig. 196 illustrates a four-pole machine, four being the [illegible] most frequently employed. Each cast-iron pole-piece which [illegible] embraces the armature has connected to it two cylindrical wrought iron cores, the outer ends of these cores being bolted to the [illegible] iron standards forming the yokes.

The two coils on each pair of cores are so wound that [illegible] similar poles are adjacent to the cast-iron pole-piece [illegible] them, thus developing a strong field from the pole-piece. [illegible] pole-pieces are magnetised in this way alternately north and [illegible] the arrangement of the entire field being that shown in fig. [illegible] where the direction of the lines of force through the [illegible] core when it is at rest and the field undistorted, is shown [illegible] rrow-heads. The lines of force enter at the outer circumference nd also at both sides of the armature.

As the diameter of commutation is at right angles to the ines of force, and as in this multiple field there are two such iameters, A B and C D, two sets of brushes would appear to be ecessary. This will be more apparent if we consider the inducive effects upon a single coil during a complete revolution. Supposing the coil to start from A, where its plane is at right angles o the lines of force, its upper portion will, in approaching the pole-piece, N, cut the lines of force from above, and in passing from N to D it will cut other lines, opposite in direction, from below, the result being that the induced current is in one direction only during the whole journey from A to D. Here the reversal takes place, for the coil, in approaching S, cuts these lines from above, and, passing S, cuts opposite lines from below, whence another continuous current is generated while the coil is travelling from D to B, where a second reversal takes place; and similarly with the other quadrants, the third reversal occurring at C, and the fourth at A. Or, viewing the matter from another standpoint, since the reversal of the current takes place at that moment when the maximum number of lines of force is projected through a coil, and as this maximum occurs at the point midway between each pair of pole-pieces (the field being still undistorted), it will be evident that the current must be reversed as the coil passes the points A, B, C, and D. Therefore, were the armature joined up in the ordinary way, one pair of brushes must be placed on the diameter A B and another on the diameter C D, to collect the current from all the coils.

FIG. 197.

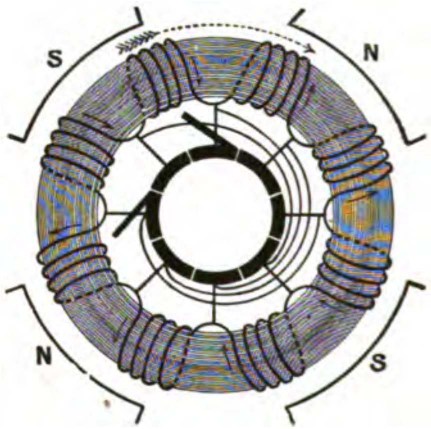


To avoid this inconvenient arrangement a simple modification is made in the winding. As every pair of diametrically opposite coils is at every stage undergoing precisely the same ind effect as the pair of coils situated at right angles to it, it follow every two such pairs of coils can be permanently joined to in parallel, for they are at every moment developing equal E. By this device only two brushes are necessary, one being s ahead of the other.

The method by which this 'cross-connecting' is effec the Victoria machine practically consists in joining togeth diametrically opposite commutator bars, as illustrated in fig.

In this machine, as in every other, the reaction of the arm distorts the field and necessitates a forward lead being g the brushes, which ever, are always rated by the same viz. 90°. It must be pointed out that are always four open to the c through the arm and that therefor resistance from br brush is but o teenth of what it be were the whole coils joined in The low resistanc obtained is an impor feature in favour of multiple pole machines, for, in order to with the ordinary ring or drum winding an equally low resista the conductor would have to be so massive that mechanical c struction would be far less easy, and eddy currents would generated in the conductor itself unless prevented by laminat

Fig. 198.



In the case of a six-pole machine constructed on similar either six brushes must be used, or, as is actually done, the c mutator segments 120° apart, joined together in threes, brushes being then employed with an angle of 60° between the

In this class of machine, however, the adjacent pole-p being of opposite polarity, must not approach each other

', otherwise an unduly large proportion of the lines of force ık across the air-space instead of passing through the armand in any case the armature must be provided with sufficient make the magnetic resistance low. Special care must also en with the lamination of the armature core. It will be bered that the eddy currents induced in a rotating core, as other moving conductor, are at right angles to the lines e of the field, and also to the direction in which the tor is moving. In the case of the ordinary simple-field ıe, the lamination of the armature presents little difficulty as es of force enter it from the outside circumference only. e pole-piece *embraces* a flat-ring armature, and the lines of nter at the sides as well as at the circumference, and it is re necessary to laminate the core in two directions, so as id currents being induced either radially or in a direction l to the shaft.

r this reason an unusually large proportion of the space the coils of a flat ring armature is occupied by insulating al instead of iron.

ferring again to fig. 197, it will be seen that the direction of es of force through the armature is, as it rotates, frequently d, and that the number of reversals per revolution would be sed by increasing the number of poles. Such changes in tisation, if too rapid, would heat the core considerably, ıpair the efficiency of the machine, and this is one reason ore than six poles are rarely employed.

g. 199 is a sectional side-elevation, showing the construction Victoria dynamo, fig. 200 being an end elevation, half in ı, of the same machine.

ıe core is built up by winding iron tape, 0·012 in. thick out half an inch wide (with thin paper insulation), round a ought-iron foundation ring, which is of the same width as the eted core, and is slotted on both edges at four equi-distant . The four-armed gun-metal spider s (fig. 200) is made in ılves, held tightly together by hexagonal nuts screwing on to aft, to which also the hub is keyed. A bolt likewise passes gh each of the arms, and when this divided spider is thus held in position, a little projection from the outer extremity

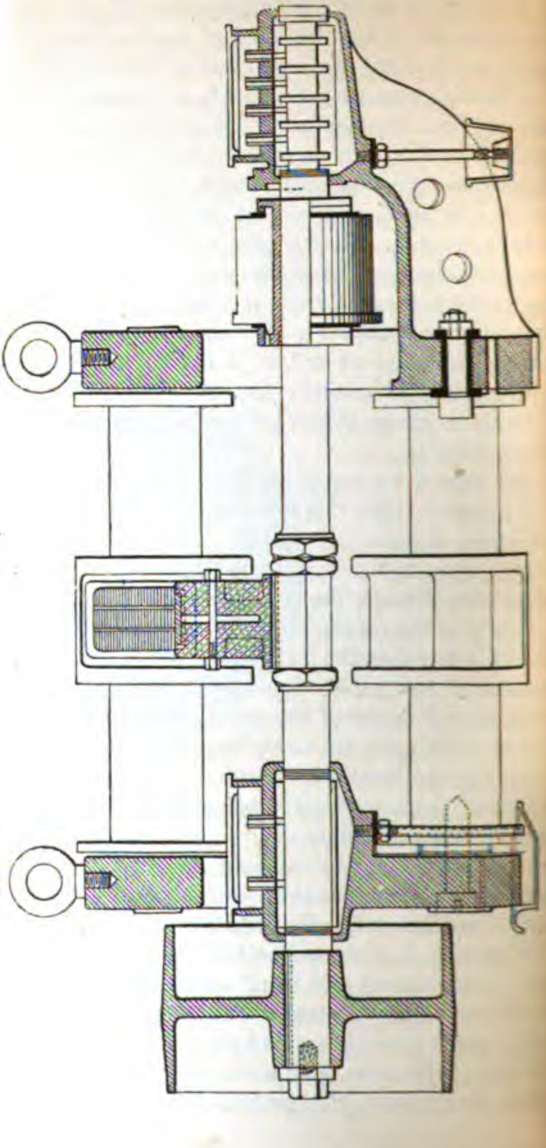
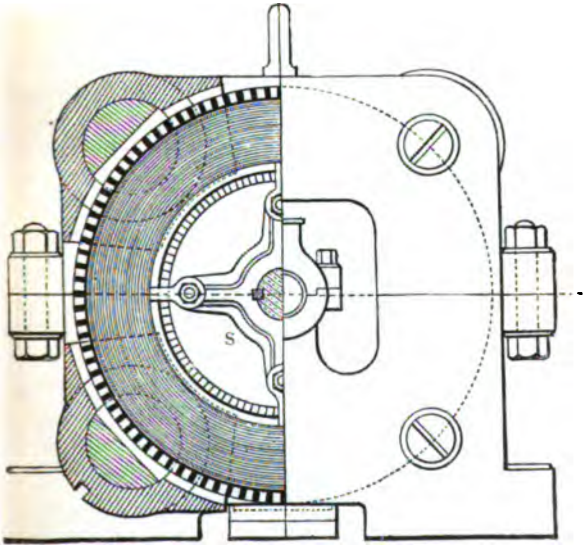


FIG. 199.

each arm fits tightly into one slot of the wrought-iron foundation g, and also extends a short distance into the core, a few of the ner layers being slotted for the purpose.

The section of the core is rectangular, and its radial depth is nsiderably less in proportion than that of the early flat ring ar-tures. Comparatively few of those lines of force which enter at outer circumference penetrate through the whole depth of the

FIG. 200.



e, and consequently the lamination near the foundation ring need be carried to a very great extent to prevent the flow of currents a direction parallel to the shaft. In some recent Victoria chines, the strips are, for this reason, narrower and more nerous towards the outer circumference than near the inside.

The armature conductor is rectangular in section, insulated h tape, and is wound in one continuous spiral round the core, connections from the commutator bars being soldered on at proper points on the inside of the ring.

The armatures of the smaller machines are, however, wound h ordinary circular wire, cotton-covered and well varnished.

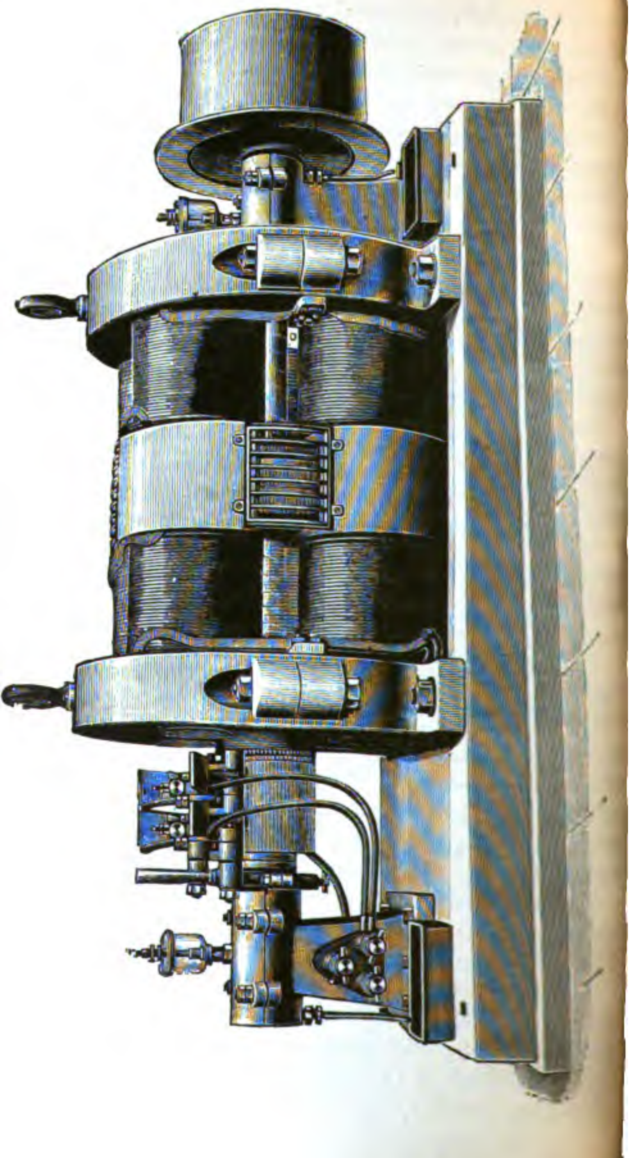


FIG. 201.

Each of the vertical standards forming the yokes is cast in two pieces, which are bolted together, so that the upper portion of each, with the two upper field-magnets, can be removed to afford access to the armature. This arrangement is shown in the figures, from which it will further be seen that the upper part of the bearings can also be detached, thus enabling the armature to be easily lifted out of its position when necessary for examination or repair.

As in all other machines, it is necessary for the space between the field-magnet and the armature to be as small as possible, and since the pole-pieces extend over the sides of the latter, it is clear that there must be no end play, or shifting of the shaft lengthways; this is effectually prevented by the long-grooved bearing shown to the right in fig. 199.

These machines are series, shunt, or compound-wound, as required. One built for the authors for educational purposes can, by means of a switch fixed on the top of the framework, be connected up for any one of these systems at pleasure.

The machine illustrated is intended to be driven at 1,000 revolutions per minute, and is then capable of developing 15,000 watts in the external circuit, at a terminal potential difference of 110 volts.

A multipolar flat ring machine is also manufactured by the Gülcher Company, and the latest type of this, known as the 'Battersea' dynamo (fig. 201), is worthy of special notice. As has been remarked, such machines, while slightly less efficient than other forms, present in some respects fewer difficulties in construction, and the Battersea dynamo is, from a mechanical point of view, as well as electrically, an exceptionally good specimen of its class.

Fig. 202 gives a longitudinal section through a machine of recent construction, a side elevation being shown in fig. 203. It is a four-pole machine, having an output of 12,000 watts.

The foundation of the armature core is the rim of a strong gunmetal wheel, which has four radial arms. The hub of the wheel bears on one side against a collar on the steel shaft, as shown to the right in fig. 202; it is held tightly in position on the other side by a steel nut which screws on to the shaft. The core itself consists of soft iron wire rectangular in cross-section, and i sulated with cotton. It is wound round the foundation-ring und high tension, the core thus built up being very strong and rigid.

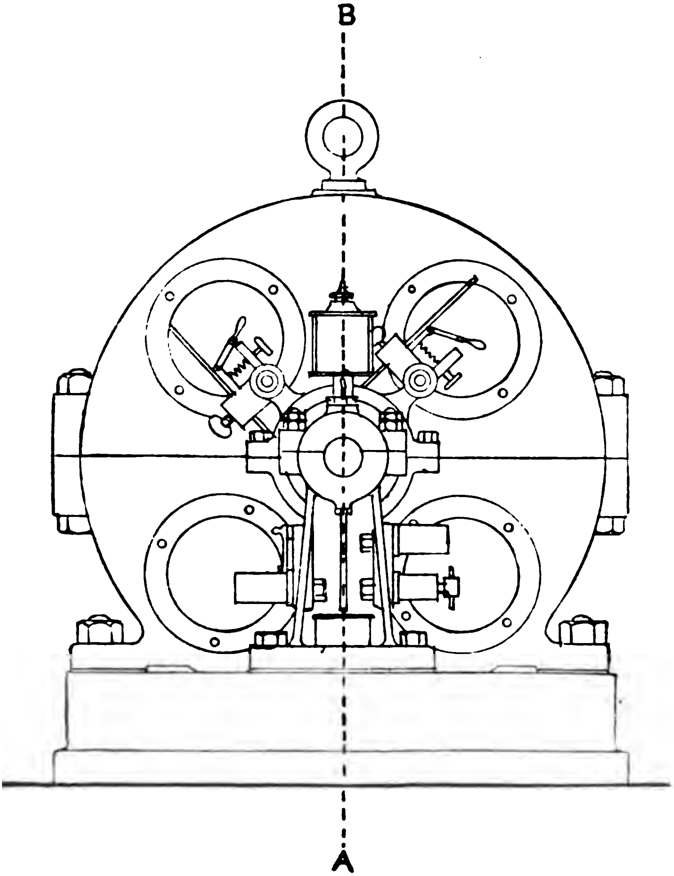
We have referred to the necessity for lamination in two dire tions ; and the smallness of the wire, and the efficiency of its ins lation practically eliminate eddy currents, while the thinness of th insulation and the tightness of the winding reduce the waste o space to the lowest possible limit.

The armature conductor, which is a copper strip, is woun over this core (embracing also the rim of the supporting wheel) i a single layer; the strip is rectangular in section, its dimension being calculated so as to just occupy the allotted space round th circumference, and thus the distance between the pole-faces an the core is made a minimum. By the device of cross-connecti the current is collected from a single pair of brushes, placed 9 apart. The method of connecting diametrically opposite pairs coils in parallel is unique. On the shaft between the armatu and commutator is fixed a wooden sleeve, over which a number flat copper rings are slipped. These rings are carefully insulate and each has two lugs projecting at opposite extremities of diameter ; a radial saw cut is made in each lug, just large enou for a copper conductor strip to be pressed in and soldered. T rings are so arranged that their lugs form a spiral round t shaft, and those connecting strips which lead from diametrica opposite coils of the armature to the commutator, are soldered the lugs of the same ring. In this way diametrically opposite ba of the commutator are joined together ; one such connection shown at the ring nearest the commutator in fig. 202.

The circular cast-iron end frames forming the yokes to t field-magnets are in two halves bolted together, the lower h being also bolted to the bed-plate, as shown in the illustratio These yoke-pieces are very massive, and, as the surfaces of cont between them and the wrought-iron cores are large and clo fitting, the magnetic resistance is low, and a large proportion the lines of force are led into the armature.

The whole armature conductor offers but little resistance, a as, by the cross-connecting, this is reduced to one-sixteenth of t resistance which would be offered were all the coils joined i

FIG. 203. *To face page* 374.



series, but little power is absorbed in the armature, and the machine is self-regulating through a considerable range.

The commutator consists of eighty copper bars, with mica insulation, fixed, as shown in the drawing, by a gun-metal nut and washer, over a gun-metal sleeve.

In smaller machines, circular copper wire, instead of rectangular strip, is employed for the conductor, and the magnetic resistance of the core is even further reduced by covering the iron wire with silk instead of cotton, the former occupying much less space than the latter.

In concluding this chapter, we may with advantage pass a few further remarks concerning the losses which reduce the efficiency of a dynamo. Omitting the power absorbed in overcoming the conductor resistance, which can easily be calculated, the losses may be classified under three general heads: (*a*) Mechanical friction; (*b*) Eddies in conductor; (*c*) Losses in armature core. The friction occurs principally at the bearings—for the commutator brushes should exert only just sufficient pressure to insure reliable contact—and the loss due to this cause increases regularly with the speed at which the machine is driven. When the conductor is massive, as in the case of a bar armature, the eddy currents in it may be sufficiently important to absorb a considerable amount of power, and, as we have seen, such conductors are frequently laminated, or sometimes braided wire is employed, to prevent the circulation of the currents. Lamination of the iron core, if properly performed, also reduces to a minimum the eddies in the iron; but there is another source of loss which arises when lines of force passing through iron are rapidly reversed or altered in direction, due to a phenomenon known as hysteresis. This loss appears to be the result of a kind of internal friction between the molecules of the iron, when they change their position, as we believe they do, under the influence of the magnetising force. At any rate, it is not possible to project lines of force through iron, or alter their position, without a small amount of work being performed independently of that resulting in eddies.

With one particular specimen of iron, through which the magnetic induction was 18,000, Dr. Hopkinson estimated that 13,000 ergs were expended in twice completely reversing the magnetism, apart from the energy reappearing as eddies. But any mechanical or other cause which sets the particles of the vibrating reduces the energy lost by hysteresis, such calculation are not directly applicable to the case of the iron employed in dynamo machine.

It is a most important matter to separate, if possible, the sources of loss in any dynamo, in order to ascertain what parts the machine, if any, need altering in design. This separation has very recently been effected practically by Mr. W. M. Mordey, who plotted his results in the curves shown in fig. 204. The machine experimented with was a direct-current Victoria dynamo, with an output of 18,000 watts, the speed being varied up to 1,200 revolutions per minute. The armature core consisted of iron strips 0·012 inch thick, with thin paper insulation, the cross-section of the iron in the core being 12 square inches, and the magnetic induction through it 12,300 C.G.S. lines.

The dynamo had four poles, and, therefore, the lines of force through the core were reversed twice in every revolution.

The machine was driven with the field-magnets disconnected, the iron having been deprived of its magnetism by a rapidly alternating current; and the power then absorbed, measured by transmission dynamometer, gave, at various speeds, the value of the power spent in overcoming the mechanical friction. Since the iron in the magnet cores always retains some magnetism, small amount of power would be absorbed in the production of weak eddy currents, were this residual magnetism not carefully eliminated.

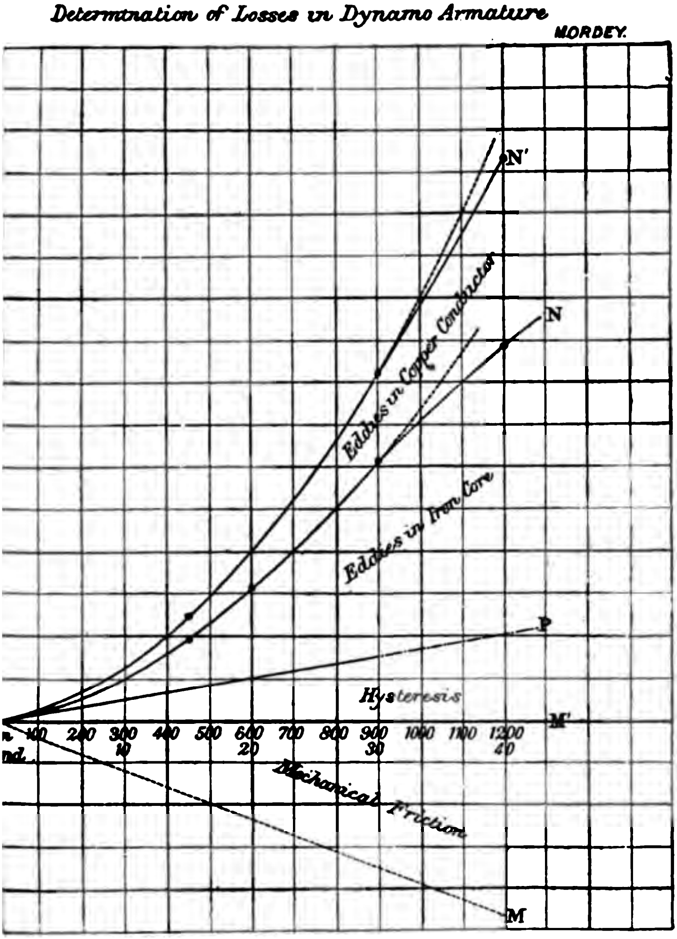
In fig. 204, O M, representing the friction loss, is plotted below the base line, so that the relation between the other curves can be more clearly seen.

In order to obtain the total losses in the iron core, the field was separately excited to its normal strength by means of secondary batteries, and the armature core, without the copper conductor, driven at various speeds, the power absorbed in driving being measured as before.

This power is the sum of that absorbed by friction, eddies in the core, and hysteresis; and by subtracting the friction the latter quantities remain, and are plotted at O N in the figure.

n winding the armature and repeating the experiments, the O N′ is obtained, and the difference between the ordinates

FIG. 204.



Determination of Losses in Dynamo Armature

nd O N represents the loss due to eddies in the copper ctor.

But the important problem is to find a means of separating hysteresis and eddy current losses in the core; this was accomplished, and the line O P represents the loss due to the former.

The method of separation is simple, and depends on the that while the loss due to the eddies varies, with a given number of lines of force, as the square of the speed, the loss from hysteresis is proportional to the speed simply.

Therefore, if two speeds are taken, such that one is double the other—for instance, 450 and 900 (see the figure)—the height of the hysteresis ordinate, from O M′ to O P, at the higher speed will be twice the height of the ordinate at the lower speed; while the height of the eddy-current ordinate from O P to O N will four times as great at the higher as at the lower speed.

After a few trials, the two points between O M′ and O N which satisfy these conditions can be found; and the line O P, drawn through these points, separates the loss caused by hysteresis from that due to eddy currents.

The curves O N, O N′, show the actual loss experimentally observed, but a dotted branch line is added to each, which indicates the curve which would be obtained if the rate of loss power had been maintained with the increase of speed up to 1,3 revolutions. It will be observed that the actual loss agrees with the calculated loss until a speed of 900 is reached, from which point it falls below the calculated value. The reason for this not altogether explainable at present, but, on account of its importance, efforts will doubtless be made to determine the relative magnitudes of the various reactions which take place.

The vertical sides of the squares represent 0·25 of a horse-power, while the horizontal sides represent 100 revolutions per minute, or 3·3 complete magnetic reversals[1] per second; and will be observed that although the lamination of the core has been carried to a high degree, yet the loss due to eddies is considerable and cannot by any means be ignored. One object of these experiments was to demonstrate that, however well laminated, the iron cores in the armature of an alternating-current dynamo the seat of a considerable amount of loss, and this has btedly been proved to be the case. The departure from the ulated rate of loss at the higher speeds, as evidenced by the ding down of the curves, prevents, however, the method being ctly applied to alternating machines, where the reversals are siderably more rapid than when the disturbing causes begin to ifest themselves. But the experimenter is to be congratulated n having produced a method which is practical, and apparently ible in the case of direct-current machines running at a fair d, and which, at any rate, forcibly draws attention to causes loss which, it is often assumed, are so unimportant that can be ignored.

---

[1] The symbol ~ is used to denote a complete alternation of the curr is, in fact, the sine curve (fig. 120) in miniature.

CHAPTER XI.

DIRECT CURRENT DYNAMOS (OPEN COIL).

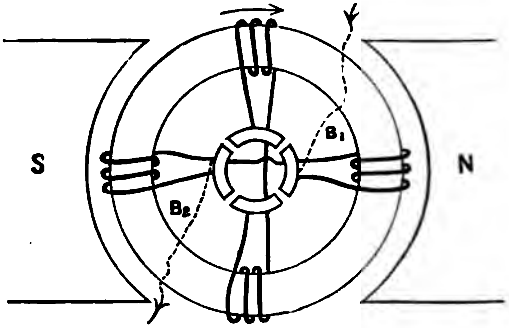
In the armatures of the direct-current machines hitherto descri all the coils are connected together, and the junction of eac jacent pair is joined to a bar of the commutator. But there is other method of constructing an armature, in which the coils kept quite separate, each having in the simplest form a sep two-part commutator. The former are known as 'closed-c and the latter as 'open-coil' armatures. Machines for develo very high electro-motive force are usually built with open armatures, an E.M.F. of 2,000 volts being not uncommon: such machines are used for electric lighting in cases whe type of the lamps and their disposition are such as to req the transmission of the current through a high resistance. closed-coil armature the E.M.F. generated by every coil in any every position, excepting at the moment when it is short-cir by the brush, forms a part of the total E.M.F. of the machine. the contrary, in an open-coil armature the current is col from a coil while it is in the position of greatest activity onl while the E.M.F. induced in it is at its maximum, the coil b thrown out of circuit during the time that it passes through period of least activity. At the beginning of this latter p another coil enters the best position, and commences to feed circuit. The coils may be wound either on the ring or d principle, but in the former case the two coils at opposite tremities of a diameter are joined together in series and ma treated as one coil.

Many of the elementary principles examined in conne with the machines already described, hold equally well for with open-coil armatures, and while it is unnecessary to ter into a lengthy discussion of these matters, we may say, briefly, at the field will be distorted in the same manner, and that e position of maximum activity for any coil will be that in which plane is parallel to the lines of force of this resultant field. To inimise the distortion and to obtain a high E.M.F. for a given eed of rotation, the field-magnets must also develop as strong a ld as possible.

The high E.M.F. developed requires, however, greater precau- ons as regards insulation than are taken with ordinary closed-coil achines, and this point must be carefully kept in view in design- ig and selecting the materials for the insulation both of the mature and of the field-magnet coils. In closed-coil machines ie potential difference between adjacent coils and commutator ars being only a fraction of the total potential difference at the rushes, the difficulties in the way of efficient insulation for high .M.F.'s are not so great as might appear at first sight. But while a closed-coil machine the number of active conductors joined series is never more than half the total, in an open-coil machine he proportion is not only greater, being usually about two-thirds, ut consists of those in the most active positions, so that the latter lass are more suited to the development of high E.M.F. It is vident, however, that if the coils are cut out of circuit while they re fairly 'active,' there must be some means of dealing with the nevitable sparking; it must either be minimised by some arrange- nent of the commutator, or its destructive action prevented.

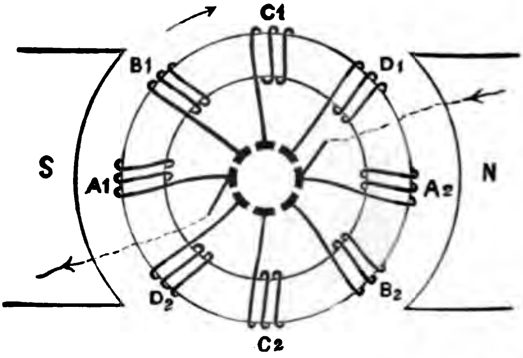
The fundamental principle of all open-coil dynamos is illus- rated in fig. 205. Two pairs of coils are shown, wound round an ron ring, at right angles to each other. The commutator has our parts, or, strictly speaking, there are two two-part commu- ators, each part forming a fourth of a circle; and each of these wo-part commutators is connected to the ends of its particular pair of coils. Two flat springs, B_1 and B_2, act the part of brushes, nd to simplify matters we will assume that the field is undistorted. Since we desire to take the current from the coils while they are at their maximum activity, the brushes must be placed parallel to the lines of force, a position exactly opposite to that of the brushes on a closed-coil machine. The two horizontal coils by this arrangement deliver their current to the external circuit, while the vertical ones, being comparatively idle, are entirely connected. The activity of the horizontal pair decreases this point, and when the armature has revolved through an

FIG. 205.



45° they are thrown out and the other coils begin to feed circuit. Each pair is thus joined up and disconnected alte for a period equal to a quarter of a revolution, and an an placed in the external circuit would indicate a current, cont

FIG. 206.



in direction, but fluctuating considerably in strength. steadiness, that is to say, a nearer approach to constancy, obtained by increasing the number of coils, although it when, on one ring, each of the brushes is resting on one sec- only, as at A, then each brush on the other ring is in contact two sections, as at B, D. The student will perceive that in the illustrated the sections of the left-hand commutator ring have ed to them the two of coils which are the intermediate ion, and therefore ire to be placed in lel, while the right- ring has joined to e pair (A) which is e best position and the pair which, inactive, is dis- ected.

FIG. 209.

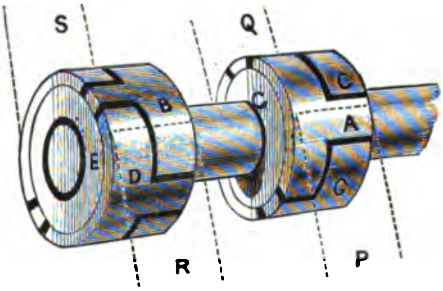
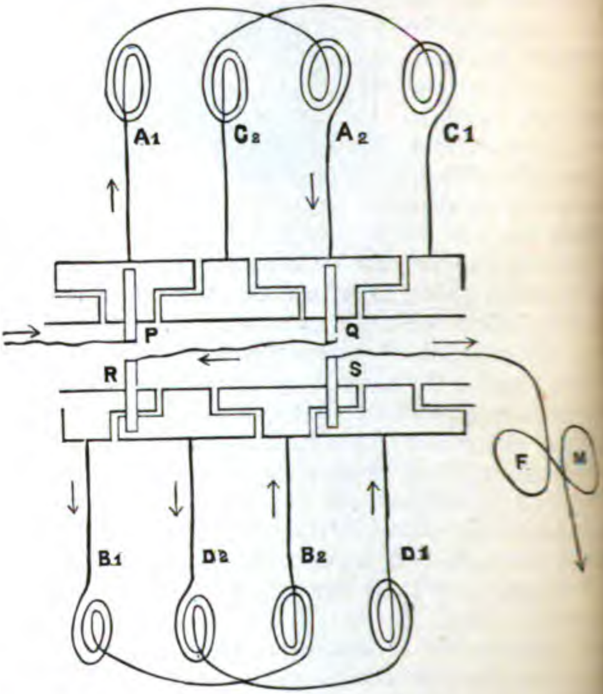


fig. 210 the two double commutators are developed or d out, side by side, to make the matter clearer, the lettering e coils being the same as in fig. 206. The path of the nt is easily traced. It passes round the pair of coils, A_1 A_2, rushes P and Q (by which it enters and leaves), each resting e section only, because those coils are in the best position. urrent then passes direct to the brush R (on the left-hand f the commutator), which, resting on two sections, affords a hrough B_1 B_2 and D_2 D_1, in parallel. The brush S, by which lly leaves, is connected to one end of the field-magnet F M ; the coils C_1 C_2 are disconnected. Such is the action takes place in a Brush dynamo having four pairs of coils in nature.

e actual machine is depicted in figs. 211 and 212, the latter ich is an elevation from the commutator end. The cores field-magnets are almost oblong in section, and are securely to cast-iron uprights which form the yokes. These two ntal horse-shoe field-magnets are placed with their similar opposite each other, and project a powerful field round the ure. There is an unusually large quantity of iron in the ure core, and careful lamination is needed to reduce the loss rgy due to eddy currents.

The method of building up this core is illustrated in fig. 210. A thin soft iron ribbon is wound in a continuous spiral round iron foundation ring A¹. Between the successive convolutions the ribbon, and held by them as the process of construction carried out, are placed H-shaped iron stampings, S, of the same thickness as the ribbon. The connecting portion of these stampings

FIG. 210.



lies wholly within the turns of the ribbon, the ends then projecting and forming spaces, as at B, within which the coils are wound. The stampings are all of one size, so that adjacent sets in the inner portion of the ring are nearer to each other than in the outer portion, while the sides of the channels in which the wire is wound are parallel. The whole is rigidly fixed together by means

ulated bolts, *b*,
ssed radially
ough the H-pieces,
spiral ribbon and
foundation ring,
as shown in the
ional view. The
pings and rib-
are, however,
ortionally much
ner, and the
ber of turns is
h more nume-
than shown in
igure. The loss
sioned by eddy
nts is thus re-
d to a minimum.
he armature
are insulated
the core by
s of canvas and
, treated freely
shellac varnish,
ayers of wire
insulated by
-cloth. The
of each pair
ls are carried
the shaft to
roper sections
commutator.
e field-magnet
re also care-
nsulated from
ores by vul-
d fibre and
ned paper, the

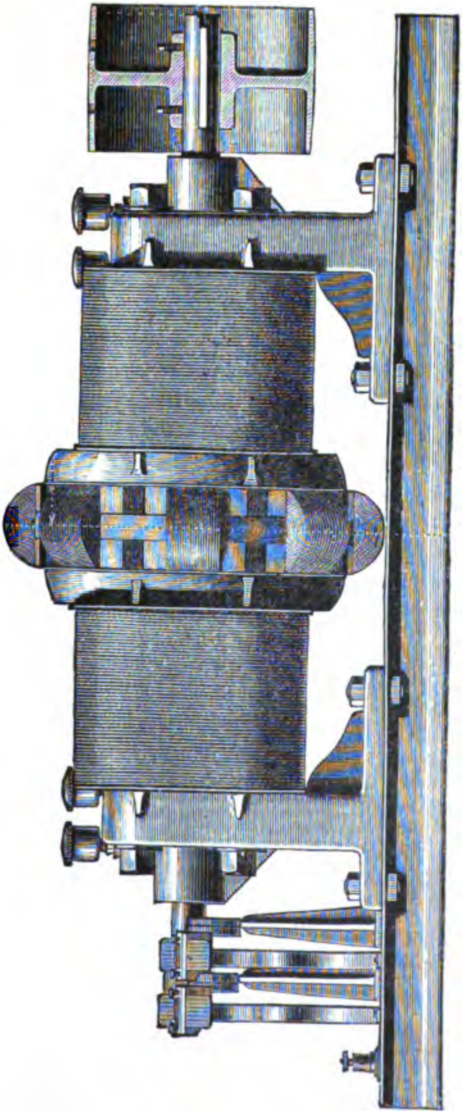
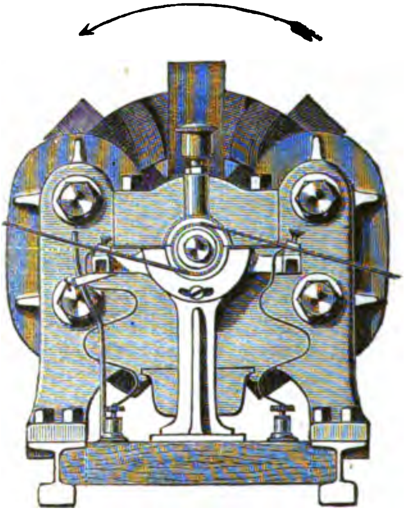


FIG. 211.

different layers being separated as in the case of the armature cotton-cloth. These coils are joined up in series, and as current generated by the machine fluctuates more or less, is a tendency for currents to be induced their unlaminated This is overcome by simple device of inter ing between the coils the iron a thin tube copper, in which the rents are induced of in the iron. These duced currents tend to duce the fluctuations the primary current.

Fig. 212.

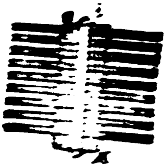


The pole-pieces tended so as to an unusually large of the armature, opposite pole-pieces similarly magnetised lines of force are not projected axially through the armature; entering the core on both sides, by the projections formed H-pieces, tend to pass circumferentially round a portion of and leave it at another set of H-pieces, near the other lines of force being in this way urged through and cut coils as they rotate.

The diameter of greatest activity is approximately in with the upper horn of the right-hand pole-piece, and the of the left-hand pole-piece (fig. 212), as will be gathered position of the brushes, the direction of rotation being left- as viewed from the commutator end. As the machine is to give a nearly constant current, the reaction of the the field, and therefore also the lead of the brushes, very slightly under ordinary changes in the load.

The machine illustrated is designed to supply 55 in series, with a current of 10 amperes. The figures awn to scale, the principal dimensions being: length of bed-ite 7 ft. 10 in., width 2 ft. 5 in., height of highest point 3 ft. 1½ in., tside diameter of armature 2 ft. 9 in. The diameter of the shaft [illegible] in., its centre being 1 ft. 9¼ in. above the ground line. The ley measures 15 in. by 12¼ in.

The brush-holders are connected to terminals on the bed-plate means of flexible copper strips, the method for adjusting the shes being shown in fig. [illegible]. Each pair is carried on a [illegible]



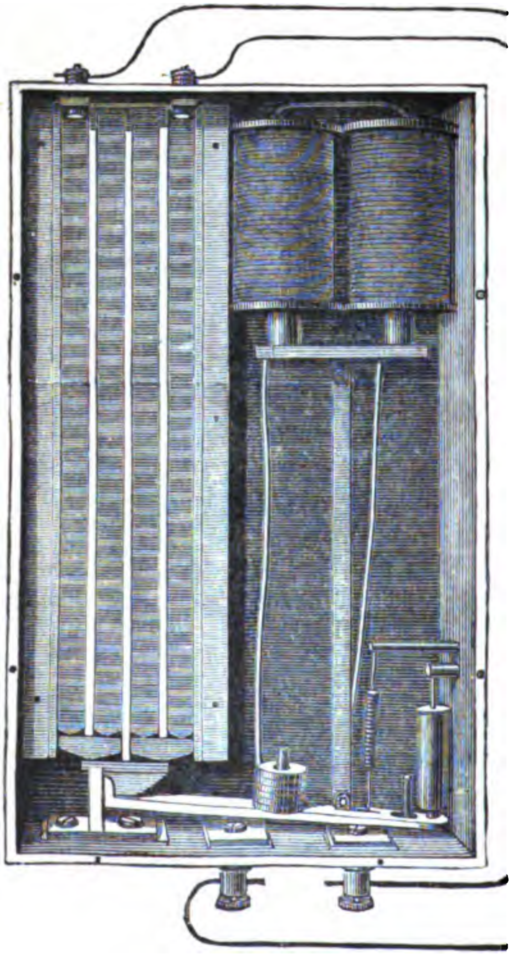
h can be turned round the shaft, its range being [illegible] ed by the length of the slot in the semicircular collar [illegible] the shaft. One end of the lever is furnished with a [illegible] ction sliding over a curved guiding-fork, the [illegible] being fixed by means of a set screw. [illegible]

Although the [illegible]

[illegible]

columns are joined in series between the two terminal screws at the top, connection being made between the two inner columns at the top, and between the outer pairs of columns at the bottom, by means of carbon slabs. Wires are led from the two top terminals to the ends of the field-magnet coils, across which these carbon columns form a shunt, whose resistance can be varied by altering the pressure upon the plates. This pressure is automatically increased when the current rises above its normal value, and the resistance of the shunt being thus reduced, a larger proportion of the current is abstracted from the field-magnets, and the strength of the field and current kept at their proper value. The method of accomplishing this is illustrated in the figure.

FIG. 214.



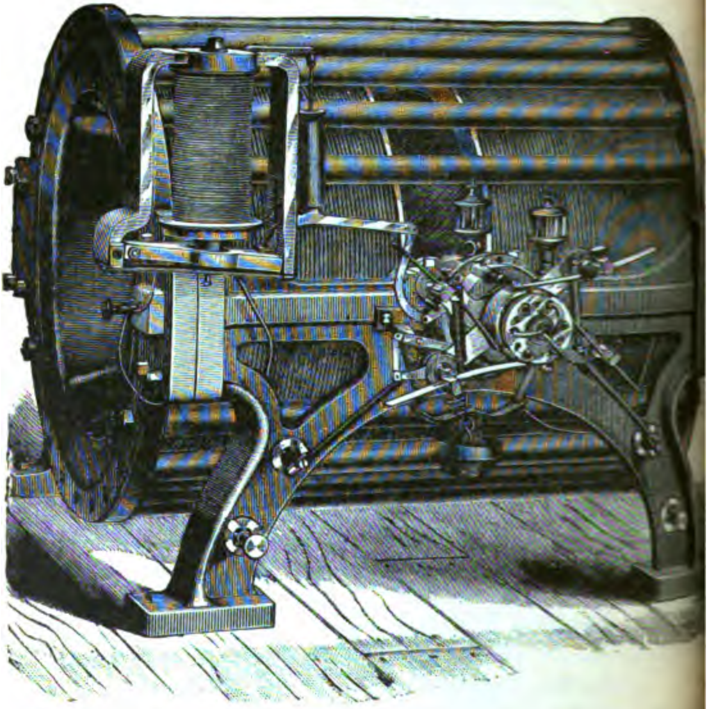
The two solenoids are joined up in the main circuit by way of the terminals shown at the bottom. Projecting partly into the coils, are two soft iron cores, permanently fixed to a common yoke-piece, the centre of which carries a brass rod attached at its lower extremity to one end of a lever, whose fulcrum is a knife-edge at its extreme left end. When by the switching out of lamps, or from any other cause, the main current passing through the solenoids increases, the cores are sucked upwards with greater force, and the block on which the four columns rest is raised through a short distance by the lever, thus compressing the carbon plates and reducing the shunt resistance, with the result that the current in the field-magnets is proportionally reduced. A dash-pot is attached to the free end of the lever to prevent sudden or jerky movements, the normal adjustment being obtained by means of a spiral spring and a few small weights slipped over a vertical pin.

Brush dynamos are made in a great variety of sizes and forms, to fit them for various classes of work, the armature being sometimes wound with twelve coils, in which three sets of commutators and brushes are required. A very remarkable machine is one constructed for the purpose of smelting aluminium, the current required being 3,200 amperes with an electro-motive force of 80 volts. Its actual speed when developing its maximum power is a little over 400 revolutions per minute. The cores of the field-magnets are of cast-iron and cylindrical in shape, with a diameter of 11 inches and a length of 16 inches, the total weight of the copper with which they are wound amounting to 542 lbs. The armature contains 825 lbs. of copper wire, and has an iron core weighing 1,600 lbs. The machine measures about 15 feet long and 4 feet wide, and stands 5 feet high.

The only other form of open-coil dynamo in general use is the Thomson-Houston, of which a general view is shown in fig. 215. It is a machine by itself, having many peculiar features, altogether different from those of any other with which we have dealt. There are two field-magnets placed horizontally, with their opposite poles facing each other. There is comparatively little iron in the cores, each of which consists of a cast-iron tube flanged at both ends, and provided at the armature end with a spherical cavity to form the pole-piece. The shape of the armature itself is that of a slightly flattened sphere, somewhat like an orange, and it revolves

between and partly within the cup-shaped pole-pieces. The
on each field-magnet core is wound in the space between
flanges, the outer flanges of the two cores being wider than
inner ones, and affording thereby, means for a number of
iron bars to be bolted through them. These bolts add
to the mechanical strength of the machine, protect the coils

FIG. 215.

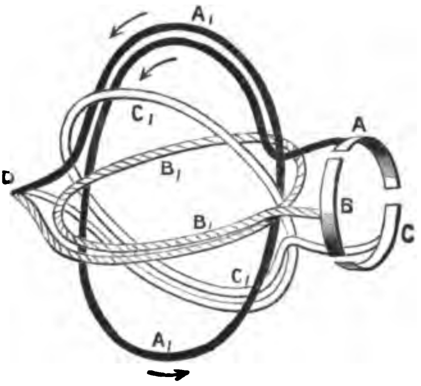


injury, and form the yoke of the field-magnets. The
which, on account of the small quantity of iron employed
construction, has but little weight, is supported by
light but strong standards, which are bolted to lateral
from the flanges of the field-magnet cores. These
carry the armature bearings.

The manner in which the armature core is built up is also interesting. Upon the shaft are keyed two stout cast-iron discs, each provided on its inner face and near its periphery with an annular groove. About a dozen wrought-iron ribs are sprung into the pair of grooves, so as to bridge the space between the discs, and form a circular framework, round which a number of layers of varnished soft iron wire is wound. This forms the complete core, into which, however, a number of wooden pegs are fixed, to guide the winding of the coils and to hold the wire in position. Before the coils are wound on, the core is insulated by layers of paper fastened by means of gum-lac.

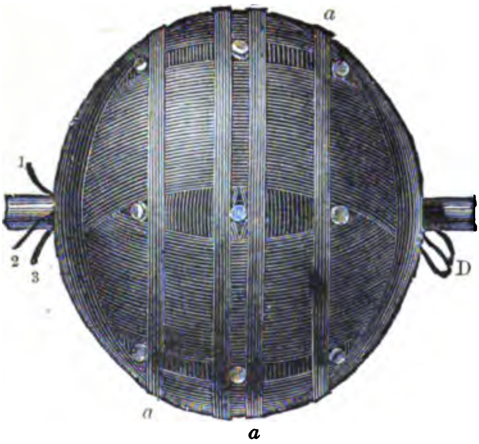
The armature consists of only three coils, and fig. 216 illustrates, in the simplest manner, the way in which they are wound. The inner ends of the three coils are soldered together, as at D, and the junction carefully insulated. Starting from this junction, each coil is wound over the core, with an angle of 120° between the middle portions of the coils, the three free ends being joined, one to each segment, A, B, or C, of the three-part commutator. A view of the completed armature is shown in fig. 217, and it will be observed that the overlapping of the coils near the shaft causes the form to become almost spherical. The junction of the three coil-wires is shown at D, the free ends, 1, 2, 3, being brought out on the other side of the armature. The coils, when finished, are bound round with four binding wires, *a a*, passing several times round the armature to prevent the coils 'flying.'

FIG. 216.



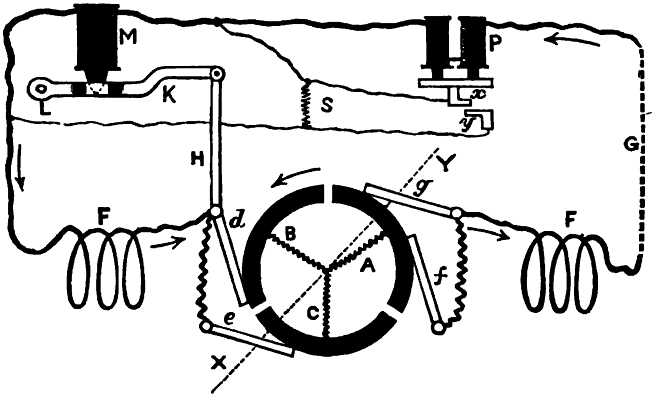
It is essential that every armature should be truly balanced, not only mechanically, but also electrically—that is to say, all the coils should be of the same area, and equidistant from the core and pole-pieces, so that the inductive effect on each is precisely the same, and they should be all of the same length and of the same resistance. It is evident, therefore, that it would be inexpedient to wind the three coils in this spherical armature completely one over the other. But the length and the average distance from the core of all the coils is made equal by a very simple method of winding. Starting at the junction D, half of one coil is wound; then, 120° further round the core, half of the second coil is wound; yet another 120°, and the *whole* of the third coil is wound. The second half of the second coil is then wound over its first portion, and, finally, the remainder of the first coil is wound over the corresponding first portion.

FIG. 217.



When the armature is rotated, currents, alternating in direction, are induced in each of the coils; the reversal, as usual, taking place in each case when the plane of the coil is at right angles to the lines in the resultant field. The reaction of the armature, of course, distorts the field somewhat, and shifts it round through a certain angle in the direction of rotation, as shown by the dotted line X Y in the lower part of fig. 218. In this figure, each radial line, A, B, C, represents one of the armature coils, united in the centre and joined to its respective commutator segment. The current is collected along the diameter of maximum activity, X Y, by two pairs of brushes, *d*, *e*, and *f*, *g*, each pair being electrically connected. The two brushes forming a pair are so placed that one presses on the commutator at a distance equal to 60° in front of the other. The consequence of this arrangement is that the most active coil is joined up in series with the remaining two less active coils, which are joined together in parallel. In the case shown in fig. 218, the coil A is approaching the best position; while B and C are in the intermediate stage, and are therefore joined up in parallel. The resulting E.M.F. is, consequently, that due to the mean E.M.F. of B and C, added to the separate E.M.F. of A. As the armature rotates, B approaches the best position, and its commutator segment alone is then in contact with the brushes *d*, *e*, while C and A, which are brought to the intermediate positions, are joined in parallel. These changes are continually repeated as the coils pass through the different portions of the field.

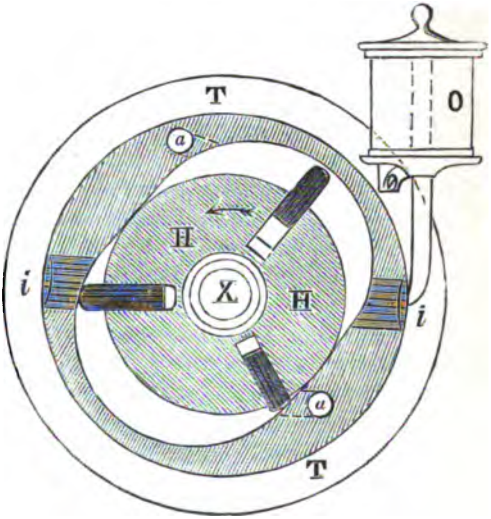
FIG. 218.



As in the case of the Brush dynamo, this machine being series wound and used on a circuit of high resistance for driving a large number of arc-lamps joined in series, the switching out of any of the lamps tends to cause an increase in the current strength, while, conversely, the switching in of lamps causes a diminution. Hence, in order to keep the current at a nearly constant strength, some regulating device is necessary. The method adopted consists in simply altering the position on the commutator of the two brushes forming each pair. It will be observed, from the commutator in fig. 218, that, the brushes being 60° apart, no coil is thrown out of circuit at any part of the revolution, and this is what we may call the normal state of affairs. When, however, current falls in strength, each pair of brushes is closed up a matically, so that all the coils are, in turn, disconnected a moment when they are passing the neutral position, and therefore nearly idle. The E.M.F. of the two coils in paral the mean of their individual E.M.F.'s, and is, obviously, low by a comparatively idle coil, so that, at the moment when the coil is thrown out, the E.M.F. resulting from the other of the coils in question is greater than it would be were they bo parallel. If this closing up of the brushes were to take p then, when the armature is in the position shown in the figure comparatively inactive coil B would be disconnected, and A joined to the external circuit in series. The maximum would be developed when each pair of brushes is so closed to form practically one brush, in which case the least acti would be always out of circuit and the other two joined series. From this point any opening of the brushes puts the coils in parallel for a greater or less interval of time reduces the E.M.F. actually developed; therefore when the c becomes abnormally strong, the brushes are opened and E.M.F., and, consequently also, the current, are reduced normal value. The motion given to the brush-holders b regulator is such that the following brush of each pair travels times as fast as the leading brush.

The brushes *d*, *e*, *f*, *g*, are mounted on a double having a scissors-like movement about a common centre. end of the lever carrying the brushes *d* and *f* is con by the bar H to the armature K, under the electro-mag This armature is hinged at L, and when the current in the circuit becomes excessive, K is attracted, *d* and *f* are draw over the commutator, while *e* and *g* are pushed forward simple combination of levers not shown in the figure electro-magnet M and the double solenoid P are both main circuit with the field-magnets F F and the lamps normally M is short-circuited by wires whose circuit may be at *x y*. The contact *x* is attached to the yoke of the tw the solenoids, and the first effect of an increase in the cu to raise the cores, break the contact at *x y*, and so cause of the current to pass through M, which then attracts K and opens the brushes. A high resistance carbon shunt is inserted at S to minimise the spark at *xy*. It will be noticed that the end of the core of M is shaped somewhat peculiarly and fits into a corresponding cavity in the armature; this shape is calculated to diminish the force of attraction uniformly as the armature recedes from the core. The regulating apparatus is shown in position in fig. 215. The small cylinder to the right of the electro-magnet is a dash-pot for steadying the movements of the lever.

FIG. 219.



There is one other device pertaining to the Thomson-Houston to which a reference is necessary, and which is employed to suppress the excessive sparking caused by cutting out the coils when fairly active and which would otherwise speedily destroy the commutator. The segments are separated by air-spaces, and just in front of each leading brush is placed a nozzle which delivers a strong blast of air at the moment that the brush breaks contact, and so actually blows out the spark. The automatic 'blower' by which these timely puffs are delivered is shown in section in fig. 219. A circular steel hub, H, is keyed on to the shaft, X, and revolves left-handedly in an elliptical chamber in the fixed box T T. Air enters this chamber through the apertures at *i i*, which are protected by wire-gauze coverings. The hub H is provided with three radial slots, in and out of which the rectangular ebonite slips can slide freely. As the shaft rotates these slips fly outwards by centrifugal force, and, pressing continually against the walls of the chamber, force th in front of them and out at the holes *a a*, to each of which is c nected one of the two nozzles above referred to. The cham is fixed to the framework of the machine in the necessary pos for the maximum force of the blast to take place at the ri moment. O is a vessel from which oil passes into the dis chamber through the aperture *i*.

The machine illustrated is designed to supply a curre about 9½ amperes to 34 arc-lamps in series. The armatu 2 feet in diameter, over all, and the resistance of the field-mag and of the armature is in each case 10½ ohms.

In addition to the dynamos which have been described in t and the preceding chapters, there are many others to whic scope of this work has not permitted us to refer, although som them are well worthy of study. We believe, however, that enough has been said to give the student a good insight int science of dynamo-building as it is now practised. Whe have given sectional views or working drawings, they have fo most part been specially prepared for this work and ref machines manufactured since the summer of 1889.

A comparison of these chapters with works of a similar cha ter published a few years ago, will show that the modern in dynamo design is towards simplification and uniform detail. As an example of the latter, we may cite the constru of commutators, in which the materials now employed are always exactly alike, while in the manner of building up the so as to prevent the sections flying out, there is very litt difference to be found. This similarity is what might, perhap anticipated, for if the vast number of experiments which been performed by the various manufacturers to determine is the best appliance to perform a given kind of work, hav equally exhaustive and accurate, an almost identical result have been arrived at. Thus, no metal has been found supe hard-drawn copper for the bars of a commutator, while extremely difficult task of satisfactorily insulating these bars case of a closed-coil commutator, nothing has been dis which approaches mica; indeed, were this mineral not it is probable that some alteration would have had to be in the general design.

reat things were at one time expected of asbestos for iting purposes, but it proved to be a good absorbent of oil as charred by the sparking, while the adhesion of metallic les abraded from the bars and brushes soon developed a r or less amount of short-circuiting with its concomitant A somewhat similar result attended the use of simple air- for insulating the bars, for the metallic dust or scrapings ulated sooner or later at the bottom of the spaces, which, numerous, were necessarily narrow. Occasionally a special is given to a commutator; for instance, that of the small shown in fig. 134 is built against the end of the armature, lividual bars being disposed radially. The object here is to the length of the machine. A special commutator is also ed with the machine illustrated in fig. 221, the object of is explained in the description.

in, the lamination of the core of an ordinary cylinder or of armature is a matter upon which little doubt now exists, for certain as it well can be that the magnetic resistance should t as low as practicable, a result only to be arrived at by g metallic continuity in the direction of the lines of force ng extremely thin insulation; while, on the other hand, the ion must be carried far enough to sufficiently reduce the rrents. Nothing better, therefore, can be devised than a thin iron plates of high permeability, separated by the possible layer of insulating material, the only doubtful eing the thickness of the plates. Such experiments as ferred to at the end of the preceding chapter may help to his point, and it is just possible that by this means some knowledge may eventually be gained which will enable the sses in the core to be minimised.

regard to the closed-coil armatures it is probable that the or ring form will in the future be even less frequently d than it is now, the drum type with a simple field, and disc with a multipolar field, having been proved to possess important advantages. Thus, again, we see that the experience is to reduce the number of types to one or inctive ones, whereas a few years ago almost every in- machine might be said to be of a class peculiar to itself. ed, the principal difference now apparent in the construction of dynamos is in the form and arrangement of the magnets, and these matters are frequently determined by circumstances. For example, one maker may have tools cap of doing a class of work altogether out of the question at an factory. Or, again, the question of weight may have to be into account, dictating the use of wrought-iron where oth cast-iron would be the more economical.

The theoretical form of field-magnet, circular in section (s to require the minimum amount of wire), and made of soft iron w out molecular discontinuity, is too expensive and inconvenient be rigidly followed, especially in large machines. Equally pow fields can be produced with rather more copper wire and a greater expenditure of power in the field-magnet coils by the partially or entirely, of cast-iron, with close-fitting joints.

The great variety in the form of field-magnets is also l due to the difference in the views of the various makers as to method of obtaining the most economical construction. Very now manufacture dynamos with the armature at the lower tremities of a pair of vertical field-magnets, where slabs of frames of gun-metal have to be interposed between the pole and the iron bed-plate, to reduce the magnetic leakage. S times this type is adopted in order to economise space and the machine as squat or short as possible, three coils being wound on the field-magnet, one on each leg and the third on we are accustomed to call the yoke.

The purpose for which dynamos are most frequently des is to light a number of incandescent lamps joined up in p circuit. It is necessary to maintain a constant potential diffe at the terminals of these lamps, say of 110 volts, and c quently the machine employed should be shunt-wound, very low resistance in the armature ; or, if the number of la likely to be subject to considerable variation, the machine be compound-wound. For the important work of 'ch secondary batteries, a simple shunt-wound machine is th suitable. A series dynamo is, of course, capable of perfo this work, but it requires to be used with extreme care, bec the electro-motive force of the cells rises, its opposition to the machine becomes more pronounced and the curre in value. The polarity of the field-magnets may, indeed, be eventually reversed, when the current from the cells will drive the machine as a motor. On the other hand, when using the shunt-machine the electro-motive force of the cells tends to increase the current passing through the field coils, whence the danger of reversal is diminished.

Many dynamos are now employed for the deposition of metals, electroplating, &c., and for this purpose they are required to furnish very heavy currents at a low potential difference. They are frequently series-wound and it is necessary that the internal resistance should be extremely low, otherwise considerable power would be wasted by the passage of the currents, which sometimes exceed 1,000 amperes. To obtain this low resistance a drum armature may be constructed with very massive bars for the active conductors, the field-magnet coils consisting of a few convolutions of massive copper band. An electro-motive force of from six to eight volts is usually ample, and this, notwithstanding that there are but comparatively few active conductors round the armature, can be obtained without the necessity for driving at a high speed. But it is not an easy matter to secure these massive bars, and consequently many machines are made with a number of fairly thick wires joined up in parallel to form one conductor. In order to reduce as far as possible the loss of energy at the commutator it is essential that the brushes should be large, and the amount of contact surface considerable. A large machine, somewhat similar in appearance to that depicted in fig. 185, has been constructed for electro-deposition work; it develops the comparatively high E.M.F. of 50 volts, and can yield 1,000 amperes at a speed of 350 revolutions.

Multipolar machines, as has already been indicated, afford a means of easily securing mechanical strength with extremely low resistance.

For supplying current to a number of pieces of apparatus joined up in series, whether arc-lamps, low-resistance incandescent lamps, or motors, it is necessary to maintain a constant current under all conditions. The two open-coil machines described in this chapter, and the dynamo illustrated in fig. 194, are suitable for this class of work.

CHAPTER XII.

MOTORS AND THEIR APPLICATIONS.

WE must now give some attention to the important clas
dynamo-electric machines employed for the purpose of converti
at any desired point, energy supplied to the machine in the f
of electricity, into energy in the form of mechanical motion.

In its widest sense this conversion rests upon the fact
whenever any of the lines of force forming part of two sepa
generated magnetic fields traverse a common space, there i
decided action between the two sets of lines, the tendency
to so alter their paths that as many lines as possible shall co
in direction. By bearing in mind this simple general rule,
difficulty should be experienced in predicting the results
will follow, even in complicated cases. This mutual action
place independently of the means by which the fields are
veloped, whether by currents in two wires (straight or coiled
or without cores), or by permanent magnets; or, the one fiel
a current in a wire and the other by a magnet. In the effo
make the coincidence a maximum, both fields are distorted
the configuration which they would independently have re
and this configuration is again assumed immediately they
removed from each other's influence. Consequently, when
lines of force pertaining to two fields approach each other,
mutual action sets up a stress, the effect of which is a tenden
impart such a motion to the material substances (whether a
bar or a conducting wire), employed in generating the fields,
make them take up positions in which the lines of force
both fields coincide to the greatest possible extent. The s
the fields, the greater is the force thus acting, and, if suffi
strong, mechanical motion is imparted to that body which

the more freely. For instance, suppose one field to be a simple one developed between the two pole-pieces of a powerful field-magnet such as has been described, and the other field to be generated by a current in a circular loop of wire. If the loop is placed vertically with its edges towards the pole-pieces, that is, with its plane parallel to the lines of force of the field-magnet, then the lines of its own field will be projected at right angles to those of the other, and the field-magnets being too massive to move, the loop will, if freely suspended, immediately turn round through 90°, when the lines of force of the other field thread through it in the same direction as its own lines. If free to move in any direction, its ultimate position of rest will be in the densest portion of the field, where the number of lines passing through it, and coinciding in direction with its own lines, is a maximum. If the current through the loop is then reversed in direction, it will turn completely round until the lines of both fields again coincide.

We have thus a means of imparting mechanical motion to a material substance, in this case a loop of wire ; and a continual rotatory motion can be maintained by reversing the current in the loop at the right moment, viz. just when its momentum has carried it a little beyond the point which, in the absence of this reversal, would be its position of rest. It remains to be seen how the principle is practically applied, on a scale such that the force with which the movable body is urged into a new position may amount to many horse-power.

Referring to the simple case of a closed-coil armature with a two-part commutator, as illustrated in fig. 149, it will be observed that if a current is sent through the two coils in parallel, while in the position shown, no movement results when the direction of the current is such that the lines of force due to it coincide in direction with those of the fixed field. This is the position of rest for the armature, and if the current in it is reversed, it will make a complete revolution until the same coincidence again exists. Now the current can be supplied by brushes pressing on the commutator segments, and so placed that each segment slides into contact with a fresh brush directly the position of rest is arrived at. By this means the current will be reversed, and a continuous rotation kept up. With only two coils, the armature might come to rest suddenly at a dead point, and would not s again from such a position ; but the number of coils can be in creased with advantage until we have, practically, an arma similar to those used in generators. On a current being se through such an armature, each coil strives to set itself with i plane at right angles to the field, in which position the coincide of the two sets of lines is at a maximum. Immediately the co arrives at this point, the current in it is reversed, causing it exert a similar force in the same circular direction, during ano half revolution.

The armature may be of the ring, drum, or flat-disc type. a it fortunately happens that most of the principles underlying design and construction of a good generating dynamo, hold eq well for a motor. The fixed field is usually supplied by pow electro-magnets as in the case of generators, these being ex by a current from the same source as that which supplies th armature. Many of the troubles which in dynamos are av or reduced by the employment of a fixed field sufficiently stro overpowet that developed by the armature, are also inhere motor, and may be avoided by the same arrangement. But i motor the question of weight is frequently of considerable i portance. For instance, the machine may be employed for purpose of propelling a vehicle, and in such cases the weig the motor is added to that of the vehicle, and involves a pro tionally increased expenditure of power in moving it. Again constructing a motor, even more care must be exercised than a dynamo, in rendering the armature able to resist sudden stresses without risk of damage, the reason for which w more apparent presently.

We have already learned that when a conductor moves th a magnetic field in such a manner that it cuts the lines of transversely, an E.M.F. is induced in the wire, this E.M.F. pending upon the density of the field and the velocity of the the cause which sets the wire in motion being quite imm And if an independent current is already flowing in the wi electro-motive force induced by the motion, will either te increase or decrease this current, according to its direction. when a wire, free to move, is placed in a certain positi magnetic field, and a current is sent through it, it quickly moves to a new position. But in the very act of moving across the field, the wire cuts the lines of force, and an electro-motive force is consequently induced in it. As such reactions always tend to stop the motion of the moving body, and as any reduction in the current must necessarily reduce the force with which the wire is moved (by the mutual action between the fields), the induced E.M.F. must oppose and reduce the current which is flowing.

In consequence of this 'counter-electromotive-force,' the current which a given external source of E.M.F. can send through a motor, varies with the speed at which the wire of the movable part of the machine is at the moment cutting the lines of force of the field. When the revolving part is forcibly restrained from moving, the current is at its maximum, being simply the quotient of the E.M.F. divided by the resistance. But when it is allowed to move, the current immediately falls in value, and the higher the speed, the feebler is the strength of the current. This may be observed experimentally by placing an ammeter in circuit with a battery and a motor, and then varying the speed of the latter.

Now, any one of the dynamos hitherto described can be used as a motor. For instance, we may take a direct-current series-wound machine, and, by simply passing a current through it from a battery of secondary cells, can cause the armature to rotate rapidly. The force with which the armature moves, depends upon the strength of the fields produced by it and by the field-magnet, and these in their turn depend upon the strength of the current.

The internal resistance of a secondary battery is very low, and if that of the machine is also low, an enormous current will pass while the armature is at rest; sufficiently strong, if maintained for any length of time, to damage it. But immediately the armature begins to move, this enormous current falls, until presently the speed of rotation and the counter-electromotive-force may become so high that only a very small current can flow, the force with which the armature turns, or the torque,[1] being, of course, also considerably reduced. This variation is extremely convenient in some cases; for example, when a motor is employed to propel a tram-car, it is required to exert very much greater power to start the car from rest, than to keep it in motion after it has been started. It is just when the car and the armature of the machine are at rest, that an enormous current can be sent through the machine, and a correspondingly great power exerted on the shaft; while the current falls to a safe value when a start has been effected, and before any damage can be done to the machine by over-heating. The necessity for its being able to resist such sudden heavy stresses as that caused by the effort to start with a heavy load, requires exceptional care to be exercised in the mechanical construction of a motor armature. Special attention is here directed to the machine illustrated in fig. 189; in which the armature conductor lies in deep narrow slots in the core, every plate of which bears directly against the shaft, the whole construction being such as to render the armature able to withstand an enormous torque without injury.

---

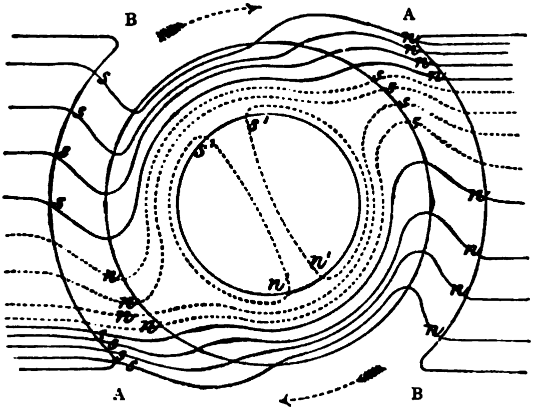
[1] The 'torque' is the moment of the force which tends to cause rotation. In this case it is equal to the length of the arm, that is, the radius of the armature, multiplied by the pull at the circumference on the conductor.

Supposing the field to be unaltered, the direction of the current in the armature of a machine when used as a motor must be the reverse to its direction when used as a generator, if the direction of rotation is desired to be the same in each case; indeed, we have just seen that the counter-E.M.F. generated is opposite to that which produces the driving current. Therefore, if the direction of the driving current is the same as that which would be developed by the machine itself, the connections of the armature or of the field-magnets of a series dynamo must be reversed; or if a rotation in the opposite direction is desired, the connections should be left unaltered, and the brushes turned round to suit the reversed rotation. A shunt dynamo, on the other hand, will, without any alteration, turn in the same direction if an E.M.F. opposite to that developed by it as a generator is applied to its terminals, for the current through the armature is then in the reverse direction, while that through the field-magnet coils is the same as before. This will be apparent on inspection of the diagrams of the shunt dynamo connections given in figs. 159 and 160; when employed as a generator the field-magnet coils form a shunt to the external circuit, but when used as a motor these coils act as a shunt, to the armature.

The distortion of the field observed when a machine is used a generator also occurs when it is employed as a motor, because, en the brushes are at zero, the lines of force of the armature d are at right angles to those of the field-magnets. But the ection of the current, and therefore of the lines of force, being ersed in the case of a motor armature, the direction of the ultant field is also different. The amount of the distortion ends, obviously, upon the relative strengths of the two fields. s very slight when the field-magnets overpower the armature, : in all cases the direction of the resultant field is such that the shes must be shifted *backward* to place them on a diameter ight angles to the lines of force, and so to avoid sparking.

The distortion of the field of a motor is illustrated in fig. 220, ich should be compared with the corresponding figure (156) for

Fig. 220.



enerator. The density of the lines of force is greater at the ns A A which the armature is approaching, and, as a conse- nce, any irregular distribution of iron in the armature core ses stronger eddy currents and develops more heat at these es, than at the horns B B from which the armature is receding, n the case of a dynamo. With an ordinary armature, however, heating is not very great, and in all cases it is influenced to a ain extent by the fact that a current of cold air is drawn in at

A A and ejected somewhat warmer at B B. In the case of a motor, therefore, this air current tends to reduce, and in the case of a generator to increase, the difference of temperature between the two horns of each pole-piece.

The current through the armature of a motor frequently varies considerably, and this may cause a shifting of the resultant field and therefore also necessitate an alteration in the position of the brushes, but in all cases a reduction in the angle of lead, and immunity from sparking with a variation of the armature current, may be obtained by employing a very powerful field relatively to that produced by the armature. But this necessitates considerable weight, especially in the field-magnet cores. Hence, the superiority of wrought-iron of high permeability is apparent, although even when this is used the weight of a motor built upon this principle is still considerable. As we shall see presently, the most effective plan of constructing a light but efficient machine is to arrange that the armature field shall be very powerful and reinforce that of the field-magnets, special precautions being taken to prevent the sparking which would otherwise ensue. But at the same time it must be remembered that the advantages accruing to the use of powerful field-magnets, even at the expense of extra weight, are not lightly to be thrown away; and that in ordinary cases it is rarely true economy to sacrifice much in order to save a little weight.

The electrical power may be supplied either at a constant pressure, or constant current; in the former case regulation is comparatively easy, while in the latter greater economy in the distribution of power can sometimes be effected. Supposing a constant potential to be maintained at the terminals of a shunt-wound motor; the current through the field-magnet coils will always be the same, and therefore the strength of the field remains constant, but the current through the armature depends upon the speed of rotation, being, in fact, determined by the excess of the applied electro-motive force over the counter-electro-motive force. Supposing the machine to be employed in driving a tram-car; then, for example, when the car commences to mount an incline, the armature shaft is called upon to perform additional work, which tends to reduce the speed of rotation; this, however, by reducing the counter-electro-motive force, immediately allows a stronger current to pass through the armature, and affords the necessary electrical power to perform the extra work. On the other hand, should the car be allowed to attain a high speed in descending an incline, the counter-E.M.F. would reach a high value, so high in fact that very little current would pass through the armature, whence very little electrical power would be expended. The demand upon the source of the electrical power is thus to a certain extent automatically regulated in a very simple manner according to the requirements, and this effect of the counter-electro-motive force obtains, whatever the purpose may be for which the machine is employed.

If the armature resistance is extremely low and that of the shunt-coils high, and if the field-magnet develops a much greater field than the armature, the variation of lead will be but slight, and further, the machine will to a great extent be self-regulating as regards speed. But since these conditions are not always obtained in a motor to the same extent as in a dynamo, chiefly on account of the anxiety to reduce the weight, few shunt motors are sufficiently self-regulating to meet all requirements. We have seen that when an additional load is thrown on the motor, the resulting reduction in speed immediately allows the passage of a stronger current through the armature; but if the speed is to be kept constant, the counter-electro-motive force also will be constant, and then the current through the armature can hardly vary at all, so that the two conditions are opposed to each other. But by reducing the strength of the field developed by the field-magnets, the counter-E.M.F. can also be reduced, and therefore a stronger current can be passed through the armature when rotating at a given speed. It is necessary, then, to devise some means of reducing the strength of the field when the load is increased and the current in the armature rises. The simplest way of accomplishing this is to place a few turns of thick wire round the limbs of the field-magnet, in series with the armature, but wound in such a manner as to magnetically oppose the shunt-coils instead of assisting them, as in the case of a compound-wound generator. The effect of these series-turns in weakening the field becomes greatest when the armature current is strongest, and *vice versâ*; but it should be observed that since the strongest current which can pass through the armature does so when it is at rest, the armature may start in either direction as determined by the shunt-coil field, or the field produced by the heavy current in the series-windings. To avoid any uncertainty, it is usual to lead the ends of the two windings and of the armature separately to the switch-board, and to reverse the current through the series-windings, so that both shunt- and series-coils act together in developing a strong field at the moment of starting, the series turns being joined up in the normal manner when the speed is above a certain value.

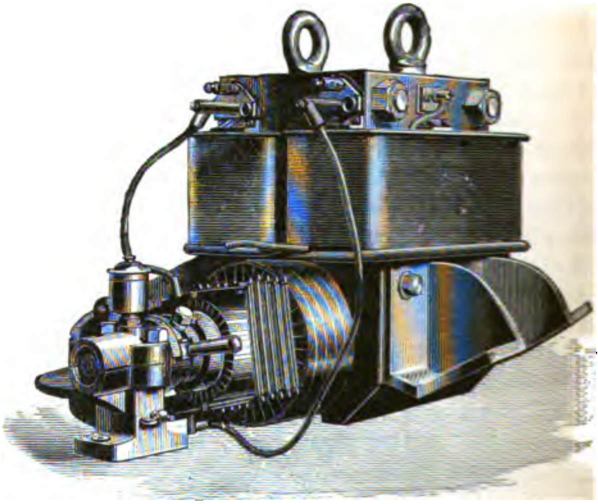
The field of a shunt motor may also be weakened by inserting resistance-coils as required, either by hand or automatically, or by altering the ampere-turns in any other manner. It appears at first sight somewhat paradoxical that the speed of a motor can be increased by reducing the strength of the field, but the reduction of the counter-electro-motive force of the armature, as mentioned above, satisfactorily explains the matter. The case for a series motor fed with a constant current is different, and the distinction must be clearly borne in mind. If the load is decreased, the speed increases, and so gives rise to a higher counter-E.M.F., but the generator responds to this and maintains the current constant. Consequently the speed of the machine increases enormously when the load is lightened to a great extent, and it is then that unless care is taken considerable damage may be done. The weakening of the field of a series motor reduces the power given out, and therefore, also, reduces the speed if the load and the current through the armature are unaltered. The alteration in the strength of the field is conveniently effected by shunting the field-magnet with a variable resistance, and the application of one such method will be considered presently. We shall also refer to the manner in which highly successful results have been achieved by means of series motors supplied at a constant potential.

Only a portion of the power given electrically to a motor is converted usefully into mechanical power, a part being spent in heating the armature, field-magnet coils, &c. When the armature is at rest the whole of the electrical power absorbed by the motor is so converted into heat, and the efficiency of the machine, that is, the ratio of the useful power obtained on the shaft to the total power supplied, is at its lowest value, viz. nought. When the armature is moved, the useful performance of work begins, and as the current also falls in strength, the power wasted in heating decreases. The higher the speed of rotation, the higher becomes the counter-E.M.F., and the less becomes the power wasted as heat in the conductors; in fact, the ratio of the power usefully absorbed by the motor to the whole power supplied, is very nearly proportional to the ratio of the counter-E.M.F., to the E.M.F. applied at the terminals of the machine. The efficiency of the machine is therefore highest when the load is a minimum, that is, when it is doing least work per revolution, while the torque, or the force with which the armature tends to rotate, is greatest when the load is sufficiently great to prevent the armature turning, and when, therefore, it is doing no external work at all. Now when a motor is running at a high speed it performs very little work indeed during one revolution, although, the number of revolutions being great, a considerable amount of work may be performed during a given interval of time, say one minute. On the other hand, when the speed is very low, the amount of work per revolution is comparatively great, but the small number of revolutions per minute prevents the quantity of work reaching during that interval a very high value. By considering these two extreme cases, it might be supposed that there is a certain intermediate speed of rotation at which the work performed by any given motor is a maximum. This is the case, and the speed of a motor at which it can perform the maximum amount of work per minute is that speed at which the counter-electro-motive force becomes equal to the electro-motive force applied at the terminals. This result is quite independent of the *efficiency* of the conversion, which, as we have seen, increases with the speed of rotation.

In fig. 221 is illustrated a motor which was constructed by Messrs. Goolden for an electric launch. The field-magnet is of the single horse-shoe shape, the cores being of wrought-iron, secured to a wrought-iron yoke-piece by two horizontal bolts. On the outer side of each pole-piece is a gun-metal supporting bracket with two flanges, shaped to fit the ribs of the boat. One bracket (that at the back in the figure) is extended on either side to form the bearings for the armature shaft.

The machine is shunt-wound, the field-magnet coils consist of 2,680 convolutions of No. 14 S.W.G., having a resistance 6·96 ohms. The armature is of the drum type, and is wound with two No. 14 S.W.G. wires in parallel, there being 216 convolutions of this double wire, giving a resistance from brush to brush o·2 ohm. Each section has six turns, so that there are thirty-s bars in the commutator, which is insulated throughout with mica The adjacent end of the armature is covered by radial extensions of the commutator bars, the mica insulation being also extended to the periphery. The other end of the armature is covered by metal plate of an equal diameter, the rest of the armature be enveloped by a waterproof material securely banded on, so the whole is rendered completely watertight. The armature s is, at the end remote from the commutator, coupled direct on the shaft of the propeller. The armature brushes and fi magnet coils are connected to separate terminals leading to controlling switch, and the motor is reversed by simply revers the direction of the current through the armature. To ren this practicable, the brushes are of a special type (see fig.

FIG. 221.



consisting of steel springs placed flat against the commutator, and provided with solid carbon blocks for making contact, the requisite pressure being given by india-rubber bands passing round hooks at the ends of the springs. This motor develops five horse-power when running at 500 revolutions per minute; the current is supplied by secondary cells, the machine being designed to carry 50 amperes at 95 volts, but the margin is such that it can safely take up to 70 amperes for several hours without risk of damage by over-heating.

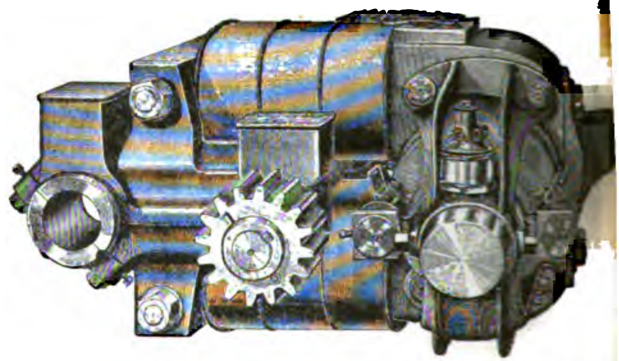
The efficiency of this motor is about 85 per cent., which is high for so comparatively low a speed as 500 revolutions per minute. In most cases the difficulty of obtaining a machine of reasonable efficiency at a low speed, without abnormal proportions and correspondingly heavy weight, renders it necessary to run at a high speed, and to effect the reduction required, by suitable gearing. Thus, for example, the wheel of an ordinary tram-car travelling at seven miles per hour does not revolve at so high a speed as eighty revolutions per minute, and it would be impossible to construct a practical motor to run at this low rate. A machine running at 720 revolutions might be employed, by introducing gearing which would reduce this speed to about one-tenth. The selection of suitable gearing is not, however, an easy matter, for it must be light, strong, and durable, and should produce neither noise nor vibration in working; and, while absorbing little power in friction, it must be capable of withstanding dust and dirt, or of being easily protected. Some very good devices, depending upon friction to transmit the power from a small wheel on the rapidly rotating armature shaft to a larger pulley on the axle, have been employed with fair success on lines where the gradients are slight; but where the power required to be transmitted is at times very heavy, this method is not to be relied on. By means of a pinion and spur-wheel, with or without an intermediate counter-shaft, very great power can be transmitted. One principal objection to this gearing is that it is noisy; the teeth of the pinion on the armature shaft also rapidly show signs of wear.

The necessary reduction in speed can also be obtained, and in a very satisfactory manner, by means of a screw and worm-wheel; an endless screw, driven by the motor shaft, gearing into the

teeth of a worm-wheel on the axle of the car or on a
shaft. Chain gearing is also employed; in this case
chain passes over a small toothed wheel on the motor sh
larger one on the axle, the teeth of the wheels fitting into
of the chain. The chain is, however, liable to stretch, a
the teeth no longer fit accurately, and slipping is like
place.

In figs. 222 and 223 a good example of spur-gearing
trated. The motor, designed by Lieut. Sprague, is inten
use on a tram-car, the field-magnet being of the single bo
type, and of wrought-iron throughout. At the yoke end th
is swung from the axle of the car, this bearing being sh

FIG. 222.

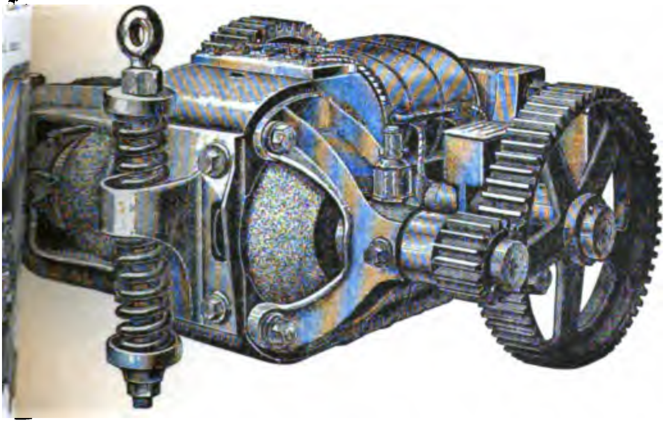


the left of fig. 222, while at the other or armature end, it is f
supported, being attached to the body of the car by means of
spring shown in fig. 223. Bronze brackets, fixed to the pole-
support the armature bearings, and a pinion on the arm
shaft, as indicated in fig. 223, gears with a spur-wheel carri
a counter-shaft which passes between the limbs of the f
magnet. At the other end of the counter-shaft is the p
visible in fig. 222, which gears into a spur-wheel keyed on t
axle of the car, the number of teeth being so proportioned,
the speed of rotation of the axle is about one-twelfth of th
the armature.

The pinion on the armature shaft is sometimes mad lcanised fibre. The wear is, of course, greatest at the this pinion, while the greatest power is transmitted by h at the other end of the train. The teeth are, however, nough to resist a *steady* pressure far greater than can be y the machine ; were the full power suddenly applied with the strain would be enormously increased, but a most nt function of the supporting spring is to prevent this lace, by yielding slightly when the pressure is suddenly

But the advantage gained in this way entails the dis- ge that the distance between the centres of the engaging is liable to variation. Consequently, involute teeth are yed, that is to say, the form of the rubbing surfaces of the is the involute of a circle, such teeth being the only ones are independent of an alteration in the distance between ntres of the wheels.

FIG. 223.



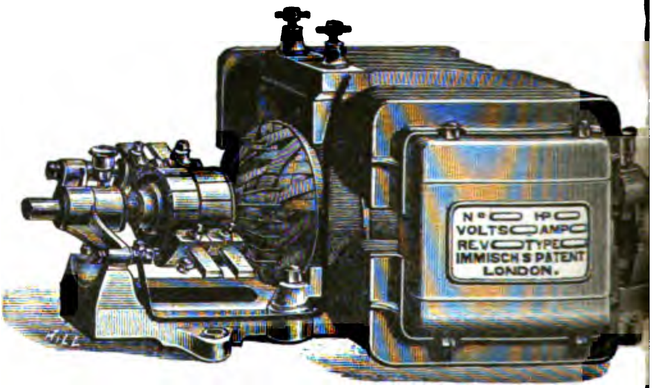
he armature is entirely covered with a waterproof material, the field-magnets being also protected by an impervious ing, the machine is but little liable to injury from moisture.

he covering of the field-magnets consists of sheet copper, oints being carefully sealed. An advantage attending this gement is, that the heavy current induced in the low resist- copper sheathing reduces to a very great extent the magnitude of the extra current developed in the coils on sud breaking the circuit.

Carbon brushes are employed, the commutator being o usual form, viz. copper bars insulated with mica.

In fig. 224 is illustrated the Immisch motor, a type wh in extensive use, and possesses some important peculiarities. field-magnets are of the double horse-shoe form, the coils wound in four sections on the horizontal portions of the although in a few instances two coils are employed, wound on vertical limbs, as in the case of the Manchester dynamo.

FIG. 224.



In these machines the magnetic field developed by the ar ture is comparatively powerful, being equal to, or even gr than, that developed by the field-magnet, the object being effect a great reduction in weight. As has been already marked, it is possible, since the two fields reinforce each oth to employ a weak fixed field and yet obtain the necessary to on the armature, provided the armature field is correspondin increased in strength; but this entails some special device avoid the necessity for altering the lead of the brushes to suit variations of the current caused by a varying load. The actual quirement is, of course, to keep the direction of the resultant unaltered, so that the brushes shall always be on a diamet right angles to this field; and in the Immisch machine the arma ment for maintaining this constancy amounts to simply short-circuiting the sections of the armature for a considerable period as they pass the neutral position. If the field is in its normal position when these coils are short-circuited, they are practically inactive. But should the field be shifted, say by an increase of the load, the short-circuited coils cut lines of force transversely, acting as the coils of a generator, and the resistance of the closed coil being very low, the conditions for a large current are established, the lines of force resulting from it being in such a direction as to oppose the distortion of the field, and bring it back to the normal position. The short-circuiting is effected by the commutator, which, as shown in fig. 224, consists of two sets of segments, placed side by side, one set being fixed half the width of a segment in advance of the other.

The armature is drum-wound, and the connections are such that the two parts of the commutator might be formed into one, by interposing each segment on one half between the two facing segments on the other half. The two brushes, side by side, are electrically connected, forming, in fact, one wide brush, and the effect is precisely similar to what would take place if an ordinary commutator were employed with thick brushes covering one bar.

Under ordinary circumstances the effect of an increase of the current in the armature would be to increase the distortion of the field, and therefore to necessitate a greater negative lead being given to the brushes. The immediate effect, however, in the present case is to cause the short-circuited coils to generate a powerful current, the lines of force due to which are in the same direction as those of the field-magnets, the resultant tendency being to reduce the distortion to its normal amount.

It might be expected that considerable heating in the coils would result from the short-circuiting, but this does not occur to any appreciable extent, and is probably to be accounted for by the prompt action of the current in the short-circuited coils in restoring the field to its normal position before the current rises to a very high value.

The armature core is built up with the usual thin iron plates, which are insulated with asbestos, thick rigid plates being placed at intervals, and having projections above the surface of the of the core, which act as driving horns.

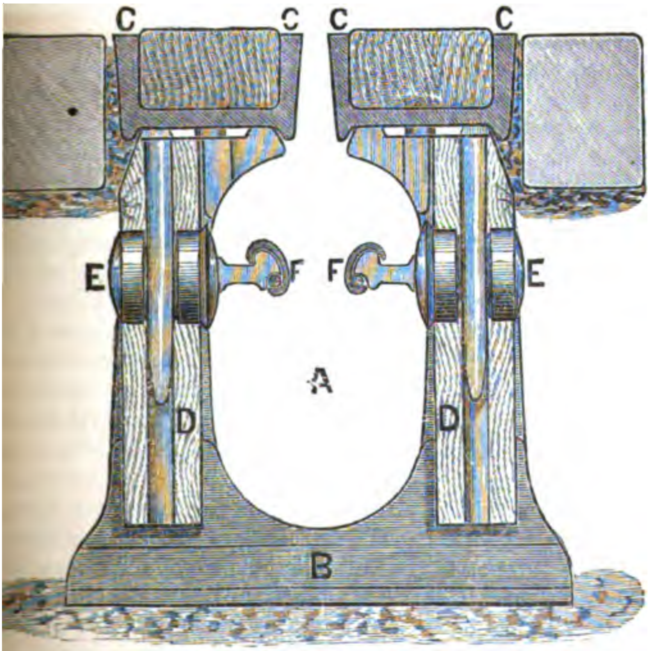
The machines are usually series-wound, and are made variety of sizes for different purposes. One, designed for dri a tram-car, weighs 5½ cwt., and is intended to run at 1,000 rev tions with a current of 40 amperes at 60 volts. The gea consists of two steel chains with a counter-shaft, the reduction speed being 10 to 1 ; the velocity of the chain on the arma shaft is, at times, as high as 2,000 feet per minute, the h speed of the motor allowing a considerable reduction in the weig of the machine. The current is supplied by eighty secondary c carried on the car, a switch being provided for connecting the all in series, or forty in series and two in parallel, so as to vary t power given to the machine. The same switch can also be us to throw resistance in circuit, when the motor is being started, t prevent the passage of a too heavy current. The direction rotation is reversed by reversing the current through the arma two sets of brushes being provided, operated by a suitable le one set adjusted with a slight negative lead in one direction, a the other set with a corresponding lead in the reverse direction.

One of the earliest and most successful applications of t electric motor was made by Mr. M. Holroyd Smith, on t Blackpool Electric Tramway. This venture was made i experimental days of electric traction, and great difficulties ha been contended with and overcome. The working has bee successful under somewhat trying local conditions as to prove t the system is sound, and we shall accordingly briefly describe main features. The line is two miles in length, and consists of of a single track with a number of pass-byes. It runs along t sea-coast in such an exposed position that the road is occasi flooded during the winter months, and at all times the s deposit, which is always prevalent near the coast, conside enhances the difficulty in insulating the conductors.

The conductors are laid underground in a channel mi between the two rails on which the car wheels run, the cur being taken from them to the motor, by means of a colle trailing through a narrow opening in the top of the channel.

In fig. 225 a transverse section of this channel is shown n support being afforded by cast-iron chairs which are fixed at rvals of a yard. One of these chairs, B, is shown in the re ; its height is 11 inches, base 12½ inches, and internal width nches ; it has vertical slots cast in it, on each side, and into these are fitted stout creosoted boards, D D, which form the sides he channel. Steel troughing, C C, runs along and is bolted to tops of the cast-iron chairs. This troughing is then filled with len blocks to form the paving of the road ; the remainder of aving being also of wood. The sides of the steel troughs slightly, so that the opening between them widens from half ch at the top to one inch at the bottom, in order that a stone fall through instead of being wedged in. The conductors trips of hard-drawn copper, of the shape shown at F F ; the onal area of each is equal to a solid rod, 0·575 inch in

FIG. 225.



diameter, and its resistance is 0·165 ohm per mile. The strip i over an iron stud, the under side of which is grooved, and wooden pin is driven in, to fix it securely in position. This stud cemented into a cylindrical porcelain insulator, E, having a d groove round its periphery, and holes 2½ inches in diameter bored in the wooden sides of the channel midway between chairs, for the reception of these insulators. A ¾-inch vert hole is also bored in the wood on one side of the insulator, a into this a wooden peg is driven, which, passing downwards thro the groove, locks the insulator fast. More recently glass st cemented into a porcelain insulator, have been adopted.

The conducting tubes are electrically connected by two wed of drawn brass (not shown in the figure), which, when driven together, exactly fit the inside of the tube, the compound we being wrapped with wire to prevent it shifting. A little spac left between the ends of adjacent sections of the tubes to allow expansion and contraction, which is, of course, considerable: an the connecting wedges cannot be soldered to the tube as the pansion due to the difference in the temperature at night and would crack the solder. The two conductors, F F, form a s positive lead, and the collector places them in connection one terminal of the motor, whose other terminal is connected the wheels of the car, the return circuit being made throug rails, or, rather, through the earth. The two tubes are elect connected at every hundred yards by a loop of insulated an sheathed copper wire, placed in a groove cut in the side bottom of the channel. The resistance of the positive lea be taken as that of the two tubes in parallel, and if the rails good earth there will be practically no resistance betwe negative terminal of the motor and the generator. But this rarely or never happen, and to avoid any resistance at the tions, adjacent rails are electrically connected by a strip of c the ends of which are plugged into holes punched in the ra

The engines and two generating dynamos are placed centre of the line. The generators are four-pole machines being separately excited by a small machine; a set of ances is placed in circuit with the exciter and field-coils, by varying which the strength of the field, and the also, the E.M.F. developed by the generators, can be altered at will. The maximum E.M.F. of each is 300 volts, and the current 180 amperes. The two machines can, if required, be run together in parallel.

The maximum potential difference, viz. that at the centre of the line, is about 220 volts, and this falls gradually towards the two extremities. The deposit of moisture previously referred to is sometimes so great as to cause a serious leakage after the line has been standing idle during the night; in the earlier days this leakage has been known to reach 100 amperes, but the passage of the heavy current rapidly increases the insulation. Such improvements have since been effected that now the loss during working hours does not, under ordinary circumstances, exceed 3 amperes.

A good idea of the salient features of the system may be gathered from fig. 226. The collector, which is designed to run equally well in either direction, consists of two slanting clearing ploughs of tempered steel, connected by hinged wrought-iron plates to a centre-piece. This centre-piece consists of a cast-iron cheek, bearing on the edges of the steel troughing, and having fixed vertically through it a strong brass strip, which is well insulated and protected by hardened steel guards where it passes through the slot. The bottom of the strip is bare, and has fixed to it a short horizontal brass arm, which carries at each end two curved hard metal wings, facing in opposite directions, and each partly embracing one of the conductors. The whole forms a combination which is flexible enough to turn sharp bends, such as those at crossing points, is capable of clearing the opening of any slight obstruction, and ensures good electrical contact with the conductors. Each of the steel ploughs terminates in a finger, on to which is hooked a hauling rope, attached to the body of the car, but a loop of weaker cord is inserted, so that if the collector meets with a serious obstruction this loop breaks, the car passes on, and can be quickly brought to a standstill by the ordinary brakes. The loop slips off the trailing finger, and a detachable electrical connection is also provided, consisting of a clip, bored to receive a heart-shaped terminal, which can easily be inserted, but requires a rather sharp jerk to release it.

Mr. Smith has invented a great number of excellent devices in

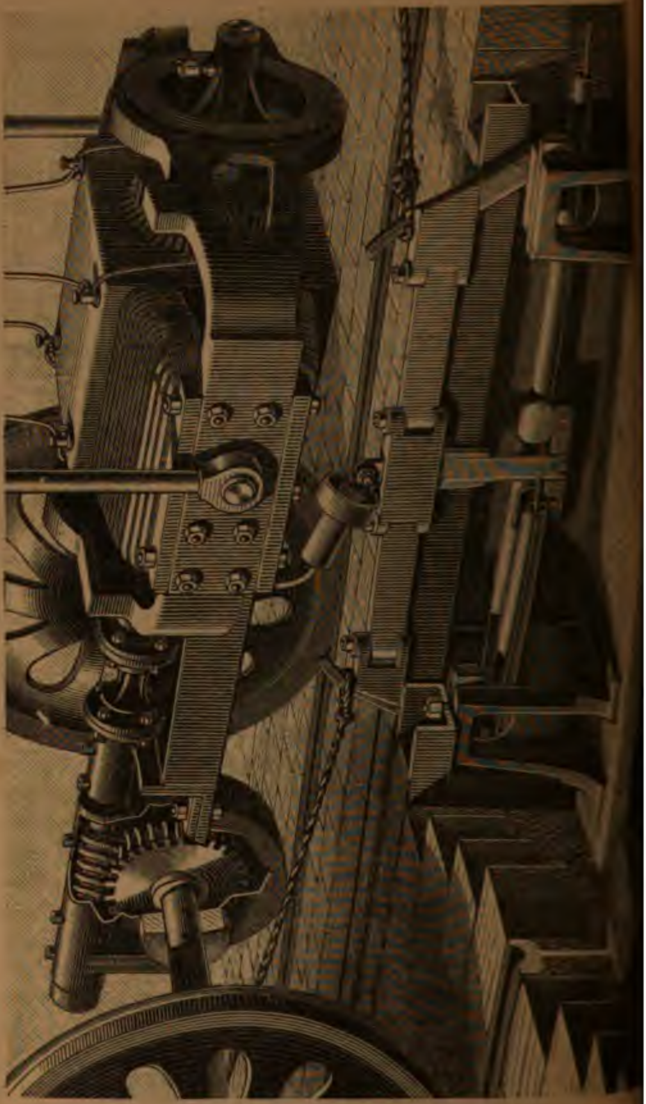
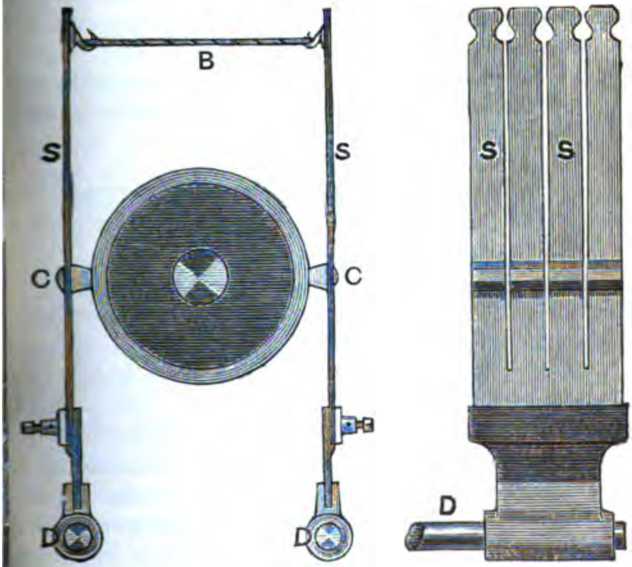


FIG. 226.

nnection with motors, motor regulation and gearing. He efers, in most cases, to work with series motors supplied at an proximately constant potential, and those employed on the ackpool line have proved very successful. Good wrought-iron employed, but no practical advantages have been sacrificed for sake of obtaining an extremely light and electrically efficient tor. The field-magnets develop a very powerful field, and the ce between the iron of the armature core and the pole-faces is

FIG. 227.

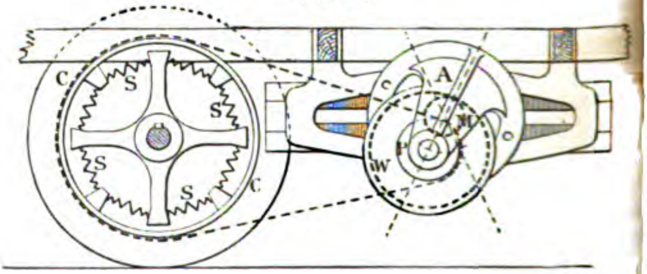


y small, the armature conductor consisting of one layer of silk-ered wire ; consequently a comparatively weak armature field be employed, and the distortion is practically nothing. In t, the brushes can be allowed to make contact at the same place either direction of rotation, without any appreciable sparking. is admits of the employment of an extremely simple and effec- type of brush, which was invented by Mr. Smith for the pur- e of enabling the armature to be run in either direction without any alteration of the brushes, and to avoid the jolting of the c breaking contact.

Two views of these brushes are given in fig. 227. D D are the spindles passing through the holders to which electrical connection is made, S S being a thin flat steel spring, divided into four strips. The extremities of the springs are connected and drawn together by india-rubber bands B, and a small block of a special metal c is fixed to the middle of each strip, forming the contact with the commutator. This type of brush is, perhaps, the simplest and most effective that can be devised for the purpose ; the wear takes place at the hard metal contact-pieces, which are so fixed that they can easily be taken out and replaced.

Fig. 226 illustrates the system as applied to a line in France, and an important feature is the worm-gearing. An endless screw gear

Fig. 228.



with a wheel keyed on the axle, and the screw is connected to the armature spindle by a flexible joint, a certain amount of play longitudinally being also provided for. The screw and wheel are effectively protected by a casing, part of which is, in the figure, removed to show the interior. This gearing is now usually employed by Mr. Smith, but that devised by him for the Blackpool line is remarkably good, and is still in use there.

The latter arrangement is clearly shown by the diagram in fig. 228, for permission to reproduce which we are indebted to the Council of the Institution of Mechanical Engineers.

A side view of the motor is shown, and M is a pinion at the end of the armature shaft, gearing into an internal toothed wheel W, that is, a wheel having teeth on its inner periphery. The

:h-circles of M and W are indicated by the dotted circles. On outside of W, that is, on the side remote from the motor, is d a chain pinion, P, gearing by a chain with a chain-wheel, C, ch is carried on the car-axle.

The chief objection to the use of chain gearing is that the in always gets slack after a time, but a very simple and effecarrangement is introduced to take up the slack and so overie this objection. The wheel W is carried by an adjustable ket or arm, A, which is centred on the motor-shaft, that is to the arm is capable of being rotated about a centre which tly coincides with the centre of the shaft. Consequently, the on M and the wheel W remain in gear for every position of the because the distance between their centres remains unaltered. arm is locked in position by bolts passing through slots, and an easy matter to loosen these, rotate the arm through a l angle, and fix it in the new position if the chain becomes :. The placing of a new chain in position also becomes a easy matter.

l special device is also introduced to avoid a jerk at starting, h, as has been remarked, throws a severe strain on the gearing. connection between the chain-wheel and the axle is not rigid, s made through several stout spiral springs which yield and the jolt off the chain when great pressure is suddenly applied. chain-wheel C C consists of a loose annular rim, having four rdly projecting pieces placed midway between the arms ting from the hub which is keyed on to the axle. The of the arms are connected to the wheel C by spiral springs s shown in the figure, and these springs extending allow the ure to be applied more gradually.

he motors are series-wound, and supplied at an approximately ant potential, and the speed is regulated by the alteration of ance joined in series with the motor; for, supposing the load : constant, any increase of resistance reduces the current ig through the armature and field-magnet coils, and so es the speed of rotation; while a reduction of resistance s the current to increase, and therefore also the speed. The resistances can also be used to regulate the strength of the nt required in starting. The aim has been to make the arrangement thoroughly practical and workable without risk error or damage by an inexperienced driver, and also to allow a variation of resistance to be made gradually, without employing large number of coils. It is also necessary to provide a surface for radiation in the case of the lowest resistances, because they have to carry a heavy current, and the heat generated considerable. All these points are effectually provided for without introducing any complication whatever. The switch is in form of a wooden cylinder with brass strips of various lengths its circumference, which make reliable rubbing contact with flat springs, when the cylinder is rotated by an ordinary lever. Only four coils of about 1 ohm resistance each are employed and by moving the switch lever the following nine changes can made in the motor circuit, either rapidly, or slowly, step by as desired. The coils are denoted by A, B, C, D.

1. Circuit disconnected.
2. A, B, C, D in series.
3. A, B, C ,,
4. A, B ,,
5. A
6. A, B in parallel.
7. A, B, C ,,
8. A, B, C, D ,,
9. Resistance coils short-circuited.

It will thus be seen that not only are the lower resistances obtained without employing extra coils, but when the heaviest current is passing the heat generated is being spent upon whole of the mass of the metal employed.

It is very significant that probably the best practical work connection with electrical traction should have been accomplished by a man who is primarily a mechanical engineer. His success chiefly due to the practical nature of his work, everything designed to suit the conditions under which it is intended employed, and the capacity of the people who are to make it. He has also devised an 'overhead' system, in which current is led to the motor by a flexible conductor, attached collector which slides over two parallel overhead conductors.

a system is less expensive in construction and easier of renewal or repair than an underground one, but is less safe, and is likely to have only a limited use on public roads in England.

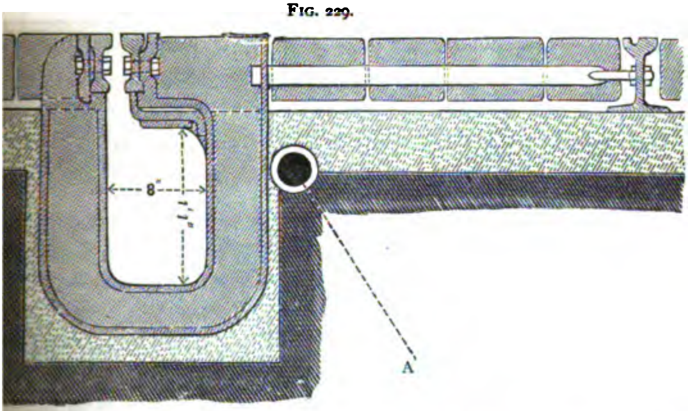
Mr. Smith has lately designed another method of constructing an underground conduit. This is in principle similar to that already described, but is expressly arranged to admit of the construction and repairs being more readily, and therefore more cheaply, executed, and also to reduce the loss by leakage. The leakage at an insulator takes place over the surface, and the resistance offered by the insulator is proportional to the length of its surface in the direction of the flow, and inversely proportional to the width of the surface. By doubling the number of insulators, the width of surface, and therefore the leakage, is doubled, so that the number of points of support for the conductor should be as few as practicable. It will be remembered that at Blackpool the insulators are only about a yard apart; in the newer system this distance is extended to about 5 yards, but then it is hardly possible to employ a rigid conductor. Steel troughing, similar to that shown in fig. 225, is used, and the cylindrical porcelain insulators are placed vertically, carrying on the underside an iron hook which supports a short loop attached to a cable. The upper side of the insulator is of rather larger circumference than the lower, and the shoulder thus formed bears upon the periphery of a hole in a stout piece of wood, placed in the bottom of the trough. This piece of wood is split longitudinally, and the two parts are pressed together (so as to hold the insulator firmly) by a wooden wedge, which is driven between the side of the trough and the wood. Over the insulator the trough is covered with an easily removable iron plate, so that any renewal can be made without difficulty. The troughing is secured to the chairs by bolts passing horizontally through a hole in the side of the trough and a vertical slot in the chair, so that by merely loosening the nut of the bolts, the trough can be lifted out, and the channel laid quite open.

A stranded copper cable is selected for the conductor, and as the distance between the points of support is considerable, the sag on this heavy cable is also fairly great. The insulators supporting the two parallel cables are not placed opposite each other, but alternately, so that the highest point of one cable is opposite the lowest point of the other. The collectors are semicircu strips, carried one at each end of a flat spring, the strips running underneath and partly embracing the cables. The flat spri presses upwards sufficiently to allow the strips to just make con tact with the cables at their highest points, and as the sagg parts of the cables are lifted up by the contact strips as they pa along a good rubbing contact is secured. For long lines one or t independent and carefully insulated main cables are also employ these being connected to the bare conductors at various points simple switches. The switches are easily accessible, and the ba conductors are divided into lengths terminating at the switches, t that any faulty length can be cut out until repaired.

A serious disadvantage attending the running of motors i parallel circuit, supplied with current at a constant potenti results from the fact that the current carried by the main lead wires is the sum of the current supplied to the whole of the moto When the number is great, this main current becomes enormo and the main conductors must be correspondingly massive, t avoid serious loss of power; and, of course, the greatest l occurs at the time when it can least be permitted, viz. when t motors are demanding the maximum current. Many difficulti disappear in a system of distribution of power to motors whi require to be supplied with a constant current, for all the machi can be joined in series, and the mains need only be of suffici size to carry the current required by one machine instead of t whole of them. But other difficulties arise, chiefly in regard t the supplying of the current to the motors, sufficiently great i fact, to make the parallel system on the whole more practi The series system has, however, recently received a promi development on a tram-car line at Northfleet, and we will bri describe the leading features in connection with this undertak

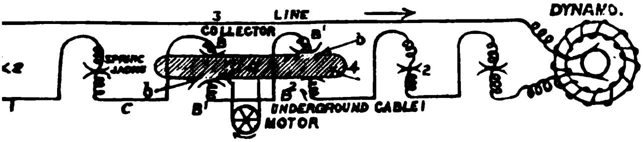
A section through the track is shown in fig. 229. Betw two rails, the outer one of which forms the tread for the car-w is an opening, ⅞ inch wide, to a conduit of the shape and dim sions indicated; the current is led from the generating dynamo conductors placed in this conduit, and thence to the moto suitable connections depending from the car, and passing thr the narrow opening between the rails. At intervals of about 4 placed cast-iron yokes or chairs, to the tops of which the two s are bolted, the walls of the conduit between these yokes being ned of Portland concrete cement. An earthenware tube, n. in diameter, is embedded in the concrete, as shown at A, l in this are placed cables forming the main conductors, the

FIG. 229.



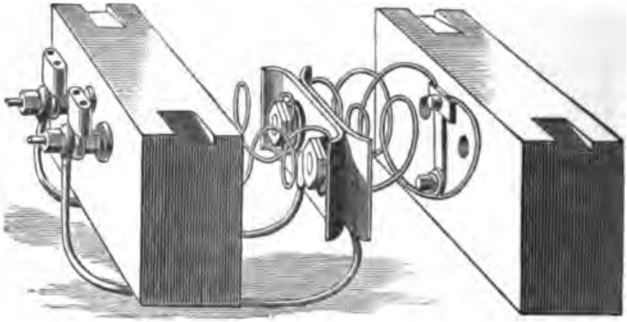
es employed being insulated with ozokerised rubber, and ng an insulation resistance of 7,500 megohms per mile. One e, marked 'line' in fig. 230, is unbroken for the whole length ne road, while the other is divided into lengths of about 21 ft. rails also are 21 ft in length, and on both sides of the joint

FIG. 230.



placed yokes, 1 ft. 5 in. apart, a chamber being formed in space between them. In each of these conduit chambers is ed an arrangement known as the 'spring-jack' (illustrated in 231), consisting of a pair of glazed earthenware blocks, suped by brackets, cast on to the joint yokes, the blocks facing each other on opposite sides of the tube. To each block is attached, by means of a double spiral spring, a gun-metal casting, curved at the ends, but flat in the centre, the springs being of sufficient strength to press the two castings together with a force of 6 lb. Two terminals are fixed on the outside of the left-hand block, each being electrically connected to one of the gun-metal strips as shown. The ends of that cable which is divided into 21 ft. lengths are connected to these terminals, so that throughout the whole of the line the gun-metal strips are in series with, and form part of, the circuit of the divided cable (see fig. 230). The current passes from one strip to the other, then by a length of cable to the next spring-jack, and so on ; it is led to the motor by forcing two conductors between the strips, these conductors being insulated from each other and joined each to one of the motor terminals.

FIG. 231.



This collector, or 'arrow,' as it is termed, is suspended under the car, and extends for its full length. It consists of two thicknesses of india-rubber belting, each having a broad brass strip riveted to it for nearly its entire length, and the nose at each end is shod with wrought-iron brought to a knife-edge, so as to easily force its way in between the two faces of the spring-jack. The maximum thickness of the arrow is 1 in., which is consequently the extent to which the gun-metal cheeks are separated. The conductor on each side of the arrow is lapped round one end, and an insulated space is left, slightly greater than the surface of contact of the spring-jack, near the extreme ends on opposite sides, as will be seen by the diagram in fig. 230, where *a* is the arrow, and *b b* the insulated spaces. In the position there indicated, the current passes from one contact strip of the spring-jack B^2, through the motor, to the opposite strip of the next spring-jack B, the strips B^1 B^1, together with the connecting length of cable between them, being cut out of circuit.

A moment later the collector will have left the spring-jack B^1 B^2, and the contact strips will fly together and complete the circuit, while the current will pass from the other strip B^1 through the motor to B, so that the current is never cut off, nor is the motor short-circuited.

The contact surfaces of the spring-jacks are placed in the middle of the conduit, and the collector arm is bent round, so that the collector also travels along the middle of the conduit; consequently the contact surfaces, not being directly under the slot, are fairly well protected from dirt or water entering from the roadway. Suitable outlets are provided for the escape of water and for the removal of any sand, stones, &c., which may accumulate, this latter operation being made easier by the fact that the conduit is empty except at the spring-jack chambers. The constant rubbing of the surfaces of the opposing gun-metal strips keeps them bright and ensures good contact when they are pressed together by the springs.

The motors are supported at one end by two bearings on the axle, and suspended at the other end by a spiral spring attached to a stout beam across the frame of the car. The speed of the motors is unusually low, viz. 400 revolutions per minute, the object being to avoid the use of a countershaft.

Worm-gearing is employed, reducing the speed in the proportion of 9 to 2; a double helical pinion on the armature shaft gears with a worm-wheel keyed on the axle, so that this wheel advances one tooth for every two complete revolutions of the armature.

The machines are series wound, and the regulation is controlled by two massive switches placed on the driving platform. In order to reverse the direction of rotation, the connections of the field-magnet are reversed by means of one switch; while the other varies the value of a set of resistance coils, which are joined up shunt to the field-magnet coils, and afford a means of weak or strengthening the field according to the power and sp required.

The current through the armature being kept constant maximum power is obtained when the field-magnets are unsh and take the whole of the current, and this arrangement w be adopted for mounting an incline, while, if less power is des the field can be weakened by shunting the field-magnets. T shunts are arranged to provide for three speeds, and, in orde stop the car, the field-magnet is short-circuited, the curren passing through the armature.

In starting a motor worked on the parallel system, ther sometimes a risk of the armature being damaged by the pas of a heavy current; for there is a constant potential diffe maintained at the terminals sufficient to determine a dange current, should the armature fail to quickly get up speed develop an opposing electro-motive force. No such danger ex in the series system, the current strength being constant unde conditions.

In the case under notice a Statter constant-current dyna employed for the purpose of generating the current. The me by which the regulation of this machine is effected has alr been fully described.

The pressure at the terminals varies from a small value nearly 500 volts, according to the demand made by the m and a considerable difference is made in the power exp by reversing the field-magnet connections on the car, wh is running down-hill and when no power is required. The of this is to turn the machine into a generator for the time its E.M.F. *assisting* that of the main generator and reduc demand made upon the latter; so that a large amount of the stored in the car during its journey up-hill may be usefu ployed, instead of all being wasted as heat at the brakes when a large number of cars is employed on an undulat this becomes an important advantage. It should be ob that although a motor supplied at constant potential, in p circuit with others, may dam back the current when the rises in running down-hill, and so absorb less power, yet it cannot actually assist the source of supply in feeding the circuit, until the speed becomes sufficient for the machine to develop an E.M.F. higher than that maintained by the generator.

An important operation in connection with a dynamo-machine is the determination of its commercial efficiency; that is, in the case of a generator, the ratio of the electrical power appearing in the external circuit and available for useful work, to the total mechanical power spent in driving the machine; and, in the case of a motor, the ratio of the useful mechanical power obtained on the armature shaft to the total electrical power absorbed. The accurate measurement of the mechanical power in either case presents some difficulty. The usual method is to employ a transmission dynamometer, or a friction brake, to determine the horse-power expended or obtained, as the case may be, but it is not possible with either class of apparatus to be certain of obtaining any but an approximately correct result. The electrical power, on the other hand, can be measured with extreme accuracy, it being simply necessary to find the current strength in, and the potential difference at the extremities of, the external circuit of a generator; and the current passing through a motor, together with the E.M.F. at its terminals; the product of the two quantities in either case, gives the power in watts.

If it were possible to arrange matters so that it would become essential to measure, by a mechanical process, only a small fraction of the total mechanical power given to a generator, say one-tenth (the other nine-tenths being measured electrically), then a much more accurate result might be obtained; for any error made in measuring this fraction, when distributed over the whole amount, would have but one-tenth the value of that which would otherwise accrue. And, further, it is far easier to accurately determine the value of a small, than of a fairly large amount of mechanical power.

An important departure, rendering such a method possible, was made some time since by Dr. Hopkinson. He takes two approximately equal machines, and, driving one as a generator, leads wires from it to the other, so connected that the current developed by the first machine drives the second as a motor.

Now, the power appearing on the motor shaft is less than spent on the generator, by an amount equal to the power abs by friction, by the heating of the various conductors, arm cores, &c., in the two machines.

But the power which does appear on the motor-shaft might be employed to assist in driving the generator; and this is by the simple process of rigidly coupling the shafts of the machines together; so that, then, the only mechanical required to be supplied and measured, is an amount equal to just referred to as being wasted in the various parts during double conversion.

This fraction, thus supplied, is conveniently measured dynamometer of the Hefner-Alteneck type, which meas directly in pounds the difference between the pull on the and slack sides of the belt, that is, the actual pull causing rotation of the pulley. This number, multiplied by the number feet travelled by the belt per minute, gives the number of pounds of work performed in one minute, which, divided by 33 gives us the horse-power supplied by the belt; since one power is a rate of working equal to 33,000 foot-pounds per With the particular dynamometer employed in one test ma Dr. Hopkinson, the pointer moved over one division of the for a pull of 2·705 lb. on the tight side of the belt in exc that on the slack side, and the radius of the pulley was s one revolution corresponded to an advance of the belt 3·63 feet; in this case, then, the work done per revolution 2·705 × 3·63 foot-pounds, for one scale-division.

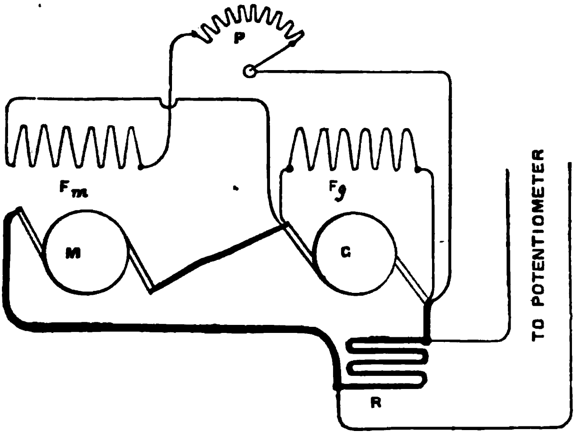
From this it will be seen that if T represents the numb scale divisions traversed by the pointer, and n the numb revolutions per minute, then the power applied $= \frac{2·705 \times}{33}$ $\times n \times \text{T} = 0·000298 \times n \times \text{T}$ horse-power.

A number of experiments were made with the machines case under notice, and, as they are interesting, the full res one test, as furnished by the experimenter, are appended.

The electrical connections were made as in fig. 232, and Fg represent the armature and field-magnet of the ge and M and Fm those of the motor. The heavy lines indic ı connections between the two machines, and, in order to sure the current, a small accurately known resistance, R, is ed in the main circuit; to the extremities of R, are connected s leading from a potentiometer, by means of which, with a k standard cell, the potential difference between the ends of esistance can be accurately measured.

'his potential difference, divided by the resistance (which was is case 0·0058 ohm), would give the current flowing through

FIG. 232.



nain wire. The potential difference between the terminals e generator was measured by a Thomson graded voltmeter, ously standardised by a Clark cell.

'ow, the two machines were exactly alike, and, consequently, ıed in opposition (as two shunt machines must be, when one juired to drive the other), and then driven at equal speeds, ırrent would flow from one armature to the other, for they l generate equal E.M.F.'s, or, in other words, the counter-o-motive force of the motor would be equal to the electro-re force of the generator. For this reason, it is necessary to en the strength of the motor field, and this was effected by ıg a set of variable resistances, P, in series with the motor magnet coils; and, by altering this resistance, the current

passing through the motor armature could be varied at ple
The motor field-magnet coils, together with P, form a shunt
generator terminals; the motor armature thus receiving the
of the current passing through R. And, since the resistan
the two field-magnet circuits are known, the current in eac
readily be calculated after the potential difference at the gen
terminals has been measured.

The resistances of the armatures and field-magnet coils of
two machines were :—

Generator . .	Armature . .	0·009947 ohm.
	Field-magnets .	16·93 „
Motor . . .	Armature . .	0·009947 „
	Field-magnets .	16·44 „

1. The two dynamos were run with brushes removed and
the fields unexcited.

Scale reading = 21·6 divisions.
Revs. per minute = 808.
Horse-power = 5·2.

2. The two fields were separately excited, and the dyna
driven, still with the brushes off, when

Scale reading . . . . . = 30 divisions.
Revolutions . . . . = 802.
Shunt current in field of generator = 6·9 amperes.
„ „ „ motor . = 6·7 „
Horse-power . . . . . = 7·169.

3. The connections were made as in fig. 232, and the foll
results were obtained :—

E.M.F. at terminals of generator . = 110·12 volts.
Main current . . . . = 358 amperes.
Current through generator magnets = 6·50 „
Current through motor magnets . = 5·36 „
E.M.F. at terminals of motor . . = 107·33 volts.
Speed of machines . . . = 764 revs. per min
Power transmitted by belt . . = 6602 watts = 8·850 h

Hence—

Total power given to generator . = 42917 watts = 57·53 h.-p.
Power lost in armature core . . = 831 „ = 1·11 „
Power lost in generator magnets . = 716 „ = 0·96 „
Power lost in generator armature . = 1360 „ = 1·823 „

And therefore—

Commercial efficiency . . . = 93·23 per cent.
Loss in core . . . . . = 1·94 „
„ magnets . . . . = 1·66 „
„ armature . . . . = 3·17 „

Similarly for the motor—

Total power given to motor . = 38886 watts = 52·13 h.-p.
Power lost in internal friction of core . . . . . = 831 „ = 1·11 „
Power lost in motor magnets . = 472 „ = 0·63 „
„ „ „ armature . = 1275 „ = 1·70 „

And therefore—

Commercial efficiency of motor . . = 93·37 per cent.
Loss in core . . . . . = 2·14 „
„ magnets . . . . = 1·22 „
„ armature . . . . = 3·27 „

The loss due to friction of the bearings and one or two unimportant causes, has then to be determined and deducted, to obtain the real commercial efficiency, which, after this deduction, was found to be : motor 92·6 per cent., and generator 92·5 per cent.

These efficiencies are phenomenal, and would seem to indicate some error in measurement ; but the method itself, being a good one, merits careful attention on the part of the student.

One disadvantage of the original method is that it is necessary to have two approximately similar machines in order to perform the test, and this is sometimes inconvenient. A number of modifications of the method have, however, been suggested, the measurement of even a fraction of the power mechanically being in some cases avoided by obtaining the extra power representing the waste by means of a small motor, and measuring the amount supplied, electrically.

Any one of the alternate-current dynamos described i Chapter VIII. can be used as a motor ; that is to say, its mova parts can be caused to rotate, and mechanical power obtained i the armature or field-magnet shaft, as the case may be, by supp ing power electrically by means of a suitable *alternating* cur Such machines have some important advantages, and some se disadvantages ; there is no doubt, however, that the latter w shortly be overcome, as at the present moment more energ being brought to bear upon the evolution of a practical altern current motor, than upon any other electrical problem.

The chief advantages are, first, that the electrical power ca better be supplied at a high potential difference with a compa tively small current, thus minimising the loss in the conduct leads ; and, secondly, that the machine is perfectly self-regu as regards speed, in spite of load variations, for it keeps pe time with the generator. Its speed can readily be varied by vary the rate of alternation of the supply current, although this me is impracticable for obtaining frequent speed alterations, or if t same generator is supplying more than one motor. The nece for an alternating motor is apparent, since so much distri for lighting purposes is now being effected by alternating cur while up to the present no satisfactory motor is available general use on such a circuit.

The principal disadvantages are that the machine cannot s itself, as can a direct-current motor, but has to be independe driven up to the speed of the generator ; while if the load is m excessive the motor stops entirely, and has to be again started some external means. The machine will, however, make g efforts to respond to the extra work thrown upon it, and to kee synchronism with the generator, but will surely fail immed the load is sufficient to drag it out of unison.

It is extremely inconvenient, and requires considerable p to start a large machine, whence any device to facilitate th very welcome. Perhaps the most practical method yet devised that due to Mr. Mordey, who employs for the purpose the s machine used to excite the field-magnets. This, as seen in fig. 140, is coupled direct to the main-shaft, and its current at times passes through and charges a small secondary battery. When the machine is to be started the current from the battery is passed through the exciter for a minute or two, converting it into a motor, which puts the alternate-current machine into rotation. As soon as synchronism between the motor and the generator is obtained, the former is switched into circuit and continues to run.

Some extremely good results have been obtained with Mordey alternators when used as motors, proving them to be all that can be desired for classes of work in which the speed does not require to be varied, or where frequent stoppages are not necessary.

From these motor properties of an alternator, results the very important fact that two independently driven alternating generators can be run in parallel, that is to say, their armatures can be connected in parallel so that the two machines can jointly supply power to the external circuit. It is, however, essential that the two machines shall give the same rate of alternation, and also run co-phasally, that is to say, the maximum positive electromotive force, and also the maximum negative electro-motive force of the two machines must coincide in point of time. Then the resultant E.M.F. is the same as that of one, while the current, and also the power developed, will be doubled. Now the remarkable fact is, that the two machines will make great efforts to keep in phase, and will do so, even if the mechanical power supplied to one is increased or diminished within a reasonable limit. To explain this extremely important mutual action we may remember that the reaction between the armature and field-magnets of a direct-current dynamo is such as to tend to stop the rotation, and this tendency becomes stronger as the current in the armature increases, while a weakening of the current of course reduces the resistance to rotation. The speed might therefore be diminished by increasing the current flowing through the armature, by some external means, while by inserting an opposing E.M.F. in circuit, and reducing the current, the speed could be increased. And if the opposing E.M.F. exceeded that developed by the machine, the current through the armature would be reversed, and the machine would run as a motor.

Now, these effects can be obtained with an alternate-current dynamo. That is to say, if the brief currents generated by are increased in strength, the tendency will be for the machine to down, while if an opposing alternating E.M.F. acts in such a as to reduce these currents, the machine will quicken its and it will run as a motor, doing work for the moment on the mover, if the opposing E.M.F. is sufficient to determine a in the reverse direction.

Now when two alternators are driven independently coupled in parallel, and one begins to lag behind the other, maximum E.M.F. of the leading machine occurs a moment than that of the other, and consequently a heavy current from the leading to the lagging machine for a very brief interval time. This current being opposite in direction to that which then being generated by the lagging machine, tends to drive it a motor and to accelerate its speed ; or if the difference of E.M. is not sufficient to set up a reverse current, it weakens the one with the effect of allowing the lagging machine to catch as already explained. On the other hand, the later occur E.M.F. of the lagging machine will tend to increase the current the leading one and so pull it up. These reactions will commence immediately the alternators tend to get out of phase, well-designed machines the effect is so prompt and forcible they run together perfectly in spite of inequalities in the It becomes very important, therefore, to decide what and peculiarities a machine should possess to fit it for working. Until recently it had been supposed that it was lutely necessary for such a machine to have considerable induction, but even then the performance was admitted somewhat difficult and uncertain. Consequently, an without an iron core, and with few convolutions, was deemed undesirable ; but these views have been somewhat shaken to a great extent, entirely reversed, by the recent researches of Mordey. That gentleman starts with the assumption that since maintenance of synchronism depends upon the motor properties the two alternators, the machine best fitted for parallel must be one which possesses these properties to a high degree

Consequently, the armature should have little resistance very little self-induction, and then the transfer of power by means of brief currents from one machine to the other, which serves to hasten or retard as required, takes place much more suddenly, and the regulating action is much more prompt and forcible. Of course, the armature will have some self-induction and some resistance, but it is satisfactory to know that neither of these undesirable factors need be made abnormally high, merely for the sake of rendering parallel working practicable. It is probable, however, that there is a limit depending upon other conditions, (such as the rate of alternation,) below which it is inadvisable to reduce the self-induction, and that some definite relationship between self-induction and resistance should exist for any given case; but, on the other hand, it is possible that this limit is very low, and that the working rule will be to make the two factors concerned as low as is practicable.

In the Mordey alternator, which has no iron in the armature, self-induction has a low value, so low, in fact, as to unfit the machine for parallel working if the old theory were correct. In order to support his views on the subject, the inventor made an exhaustive series of tests with two of these machines, each being similar in appearance to that depicted in fig. 140, but having an output of 50 horse-power, with a maximum E.M.F. of 2,000 volts, at a speed of 120 revolutions per minute. The details of one set of tests are given below. It should be noted that the machines were driven by two independent engines, not connected in any way, and provided with heavy fly-wheels; each engine also drove a heavy set of countershafts, fitted with a number of belts, &c., so that the momentum was considerable.

1. The alternators were run up to full speed, and each excited to give 2,000 volts. When in phase they were switched in parallel without any external load, and without the insertion of any self-induction coils or resistance between them. They ran in parallel perfectly.

2. A considerable inductionless load was then put on, varied, and taken off. They ran equally well under all circumstances.

3. They were uncoupled, and then, the load being connected to the mains, they were suddenly and simultaneously switched in parallel and on to the mains with perfect success.

4. One alternator was excited to give 1,000 volts, the other giving 2,000 volts. They were then switched in parallel, and went into step perfectly, giving a terminal potential difference of about 1,500 volts. No extra self-induction or resistance was inserted in this or in any other case. A load was then put on without affecting their behaviour.

5. With one machine at 1,000 volts and the other at 2,000 volts they were switched in parallel when out of phase, and instantly went into step. A large current appeared to pass between them for a fraction of a second, but not nearly long enough to enable it to be measured or to do any harm.

6. They were then left running in parallel while one was disconnected from the engine, by its belt being shifted from the fast to a loose pulley. It continued to run as a motor synchronously. A load of lamps was at the same time on the circuit.

7. The two machines were then uncoupled and excited up to 2,000 volts. They were then switched in parallel when out of phase and without any external load, and went into step instantly.

8. Whilst running as in 7, steam was suddenly and entirely shut off one engine. The alternators kept in step perfectly, one acting as a motor and driving the large engine and all the heavy countershafting and belts. It was impossible to tell, except by the top of the belt becoming tight instead of the bottom, which machine was the motor.

To find the power exerted by the alternator acting as a motor in 8, a direct current motor was put in its place, and the power required to drive the engine and shafting was found to be [illegible] horse-power.

The above results speak for themselves; but a word of explanation may be given with respect to No. 5. There is an E.M.F. in excess, of 500 volts, which would be competent to send [illegible] enormous current through the low resistance of the two armatures, the low self-induction not being able to prevent it, even though it is only applied in the same direction for a very brief moment. No such dangerous current was observed, and there must evidently be some other cause to prevent or modify it. The rather interesting point has been very simply explained by Sir William Thomson, who points out that the effect of a sudden rease of the current at any instant through the two armatures, in direction determined by the excess of E.M.F. of the more rerful machine, is to tend to increase the strength of the field the weaker, and to decrease that of the stronger machine. So : although a strong current would be started round the two tures, its effect would be to immediately strengthen the field the 1,000-volt and oppose that of the 2000-volt machine, until E.M.F. developed by each would have nearly the same value, 1,500 volts. This brief equalising current would pass twice every complete alternation.

CHAPTER XIII.

TRANSFORMERS.

WHEN it is desired to convey energy to a distance by means of electricity, either for the purpose of producing light or mechanical motion, the chief problem to be faced is, how to reduce to a minimum the waste of energy during the transmission. We have seen that when a wire is used to convey a current, the rate at which energy is lost in that wire can be measured by multiplying together the current strength in amperes and the difference of potential between the ends of the wire in volts, the result being the number of watts so expended. And since the electro-motive force is equal to the product of the resistance of the wire and the current flowing, the loss in watts may also be calculated as the product of the resistance and the *square* of the current strength. That is to say, in the first place the power expended in any part of a circuit is proportional to the resistance of that part. Suppose, for example, a dynamo were employed to furnish current to a number of lamps arranged in parallel, their joint resistance being 10 ohms; then if the resistance of the machine and leads or connecting wires were also 10 ohms, exactly as much power would be wasted, as would be usefully expended in the lamps, a state of affairs which manifestly could not be tolerated. If the resistance of the machine and leads were reduced to 1 ohm, then the power wasted would be one-tenth of that usefully employed, and so on.

The resistance of the combination to which power has t supplied is, as a rule, extremely low; and when the lamps or m are joined in parallel, the current carried by the mains is eq the sum of that required by the whole of them. Consequent resistance of these mains must be kept extremely low, a sma tion of an ohm in fact, otherwise the proportion which the power wasted bears to the total quantity of power developed becomes excessive. To keep the resistance low copper of high conductivity must always be employed, but the practical limit as regards sectional area is quickly reached on account of the high price of that metal.

Speaking generally, it may be said that transmission of energy to any distance by electricity is not economical, if we depend upon reducing waste merely by increasing the conductivity of the leads. Again stating the case as:

$$\text{Watts lost} = \text{C}^2\text{R},$$

where R is the combined resistance of the leads and generator, we see that the only other way out of the difficulty is to reduce the current strength.

If this can be done the advantage is very decided, for, by halving the current, the power wasted in any portion of the circuit is reduced to one-fourth. It may not, however, be evident at first sight, how with this reduced current the same amount of energy can be transmitted in an equal time.

Digressing for a moment, in order to introduce an analogy, the student will probably be aware that in transmitting power mechanically to a distance by a slowly moving cable, it is imperative that the cable and the rest of the moving parts shall be very strong and massive, and consequently the power lost by friction, &c., becomes enormous. But the energy transmitted per minute is equal to the pull on the cable in pounds, multiplied by the distance in feet through which the cable moves in a minute; so that, by increasing the velocity of the cable, the strength and size of it and of the other moving parts can be correspondingly reduced without reducing the amount of energy transmitted per minute. It is in fact possible to transmit enormous power by means of a light wire cable, if it travels with sufficient rapidity; and the loss due to friction is obviously reduced with the reduction in size and weight of the moving parts. Even if it is essential for the power so transmitted, to be taken, say, from a slowly rotating wheel, it is still economical to transmit it at a high velocity, and effect the necessary reduction in speed by suitable gearing.

Somewhat similarly, very great power can be conveyed elec cally by a comparatively small current traversing a thin wi only the electric pressure or potential difference is sufficiently for the power in watts may be calculated as the product of the two factors, and no difference in the amount is made by redu one of them, if the other is increased in like proportion.

But unfortunately it rarely happens that electrical power ca be utilised at a high pressure ; for instance, 110 volts is usu the maximum pressure required by a set of incandescent la joined up in parallel, and consequently it becomes necessary employ, if possible, some arrangement which shall perform the sa function as does mechanical gearing in reducing speed. That to say, we require some apparatus competent to receive electri power in the form of a small current at a high potential differenc and again give out that power in the form of a heavy current an at a correspondingly lower potential difference.

It is possible to construct such apparatus ; and before pro ceeding further we may notice the two chief points to be borne mind in designing it :—

1. The proportions of the parts must be so calculated th the reduction is effected in the desired ratio ; or, the valu the resulting potential difference must be the required fraction that applied to the apparatus.

2. The loss in power during the conversion must be kept low as practicable ; that is to say, the design must be such the efficiency of the apparatus is high.

The conversion from a high to a lower potential is rende possible by the fact already fully explained, that by starting stopping a current in a circuit, a brief current can be induced neighbouring wire. The circuit in which the original curre started or stopped is called the 'primary' circuit, while th which the currents are induced is called the 'secondary' circu

In order to obtain the maximum effect, it is necessary arrange that the secondary circuit is cut by as many as possib the lines of force generated by the primary. The best metho to wind the wire in two coils, and placing them close toge provide plenty of iron in the vicinity in order to make the p lines of force extend out beyond the secondary coil. T should in fact form a closed magnetic circuit of low resistance, embracing both coils. But since the rapid reversals of the current generate eddies, the iron must be carefully laminated ; in any case, a certain amount of power is wasted by hysteresis.

Suppose the number of convolutions in the two coils to be equal ; then by sending a rapidly alternating current through the primary, an alternating current of about the same strength might be obtained in the secondary. Again, the secondary might consist of a great length of wire in many convolutions, thin wire being employed to enable it to be kept near to the primary. In this case the primary lines of force would cut the secondary circuit many times, and the induced E.M.F. would be much greater than that urging the current through the primary. But since the power obtained from the apparatus cannot be greater than or even equal to that given to it, a corresponding reduction in the other factor would be observed ; in other words, while the E.M.F. had been enormously increased, the current would have been far feebler than that in the primary.

The student is probably familiar with a piece of apparatus known as an 'induction coil,' in which a rapidly interrupted heavy current of low E.M.F. is passed through a few turns of wire, adjacent to an enormous number of turns of finer wire. A bundle of thin varnished iron wires serves as a core, and a very feeble current of extremely high E.M.F. can be obtained in the secondary circuit. Such apparatus has proved of extreme value in experimental researches ; but it can hardly be said to have any very great importance from a commercial point of view.

We are far more concerned with the effects obtained by proceeding in the reverse order, viz. by making the length of the primary much greater than that of the secondary.

Supposing, for instance, we use the fine wire coil of an ordinary induction coil as the primary, and the thick wire coil as the secondary ; the former offers considerable resistance, and it will require a high E.M.F. to send an alternating current of even feeble strength through it. But on measuring the resulting current in the thick wire coil (now being used as the secondary), it will be found that while the E.M.F. is low, the current passing through this low resistance circuit is comparatively very heavy. It is a most important fact that by constructing such an induction coil so nearly all the primary lines of force can effectively cut the secon ary, the secondary E.M.F. can be made to bear nearly the sa ratio to the primary E.M.F. that the number of convolutions in one coil bears to the number in the other. Therefore, by mak the resistance of the magnetic circuit, and the electrical resista of the secondary circuit, both very low indeed, we can obta the terminals of the latter, an alternating potential difference wh average value is almost equal to a definite fraction of the averag of the alternating potential difference maintained at the pr terminals.

For instance, if the primary consists of 1,000 turns and secondary of 10, and a current of 1 ampere passes through primary coil while the potential difference is 500 volts, then secondary current may be 100 amperes, and the induced E rather less than 5 volts. This is the important case with which have to deal, for it thus becomes possible to effect the much-de object of transmitting electrical power at a high electrical pres and employing it at the required point at a lower pressure. piece of apparatus which is capable of effecting this transfo tion from high to low E.M.F., is called a 'transformer.'

The first transformer was constructed in 1831 by the imm Faraday. The principles which he then discovered, of the markable action of a varying current upon an adjacent circuit of almost inconceivable importance; while the method of structing his original transformer, which we shall briefly desc was well abreast of the then existing practice.

Faraday procured a welded ring of soft round bar iron, ⅞ thick, the external diameter of the ring being 6 inches. R one part of this ring he wound about 72 feet of copper $\frac{1}{20}$ inch in diameter, in three superposed helices, the distance ro the ring thus covered being about 9 inches. The wire was the first helix being insulated from the iron by a layer of calico twine was wound side by side with the wire, to prevent co between adjacent convolutions. Then followed another laye calico, over which was wound the second helix, insulated twine similarly to the first, then another layer of calico fol by the third helix, the whole being covered by calico. The of each helix were brought out so that the three coils could be used separately, or conjointly, in series or in parallel.

On the other half of the ring a length of 60 feet of copper wire was wound in two equal helices and insulated in precisely the same manner as before. These two coils were joined in series and connected to a galvanometer. The other three helices were also joined in series, and a battery connected up to them. The immediate effect of making this latter connection was seen in a violent deflection of the needle of the galvanometer placed in the 'secondary' circuit. The needle quickly came to rest at zero, but was deflected momentarily in the opposite direction on the battery being disconnected from the primary circuit.

The lines of force of the current in the primary coil were, of course, conducted by the iron ring round through the secondary coil, and the sudden cutting of this coil by them gave rise to the observed currents. As might be expected, however, a great many of the lines of force did not reach the secondary coil, and Faraday obtained a more violent deflection with the same primary current and shorter lengths of wire, by so arranging the two circuits that nearly all the lines of force generated were able to cut the secondary circuit. He disconnected the two helices which in the previous experiment were used as a secondary circuit, and in their place took two of the three superposed helices on the other half of the ring, joining them in series and to the galvanometer. The battery was then joined to the third helix, which formed the primary circuit, and although the lengths of wire were so much shorter, rather better effects were obtained, because of the increase in the percentage of the lines of force usefully employed. Had Faraday supplied the primary circuit with a rapidly alternating current, he might have obtained an alternating current of half the strength, and of corresponding higher electro-motive force in the secondary circuit; but his galvanometer would not have indicated the presence of this current if the reversals were too rapid to give the needle time enough to move with each pulsation. By using one helix for the secondary and two for the primary, the secondary current might have had twice the strength of the primary.

We may repeat that a transformer should be so designed that it can effect the required reduction from high to low E.M.F. with as little waste as possible. The wires of the two circuits sh be so disposed with respect to each other that the greatest pos number of the primary current's lines of force cut the secon circuit, while if iron is employed to assist in this direction, must be taken that but little energy is lost in it by eddies hysteresis.

To reduce the loss by eddies the iron must be lamin right angles to the path they tend to take, while it must be far as possible, continuous in the direction of the lines the Loss by hysteresis requires careful consideration; it in with the rapidity with which the current alternates, and wi density of the lines of force through the iron. Consequen should be taken in deciding upon the rate of alternation, a mass of the iron to be employed; but these are matters upon reliable experimental research upon a practical scale is needed. Attention must also be devoted to such po economy of construction, efficiency of insulation, and the for the escape of the heat which is the evidence of the in loss during the conversion.

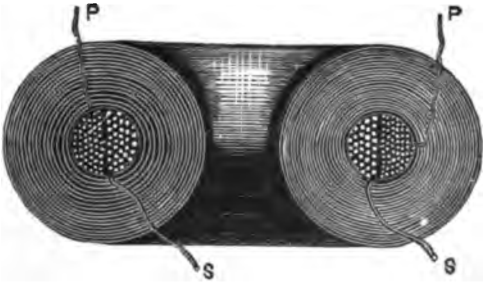
Perhaps the simplest type of practical transformer is modification of Faraday's original one. An iron core entirely overwound with a few layers of thick insulated cop to form the secondary circuit, and a number of layers of wire then wound over this to form the primary. Resista comparatively small importance in the primary coil, bu be kept low in the other coil, because that carries a heavy

It might be thought that some advantage would be de interlacing the two coils so as to bring them into closer but this cannot be done in practice on account of the di maintaining effective insulation. The potential difference even the extreme ends of the secondary coil is low. trouble is experienced in insulating this coil, but quite obtains with the primary. The wire-covering must not be otherwise the space occupied becomes great, but the must be taken to avoid bringing into proximity any co separated from each other by a long length of wire, an having a high potential difference between them. practice the secondary circuit is sometimes led into ı be and is handled, every precaution must be taken to ually insulate it from the primary. For this reason the two are never interlaced, but are wound separately, with effective ıtion between them.

he simplest way of laminating the iron core, is to build it up n iron wire, in exactly the same manner as the core of a me ring. In fact, a Gramme ring armature having a large er of convolutions can be readily turned into a very fair ormer, by using two or three equidistant sections for the lary coil, and the remainder in series for the primary. ormers are sometimes so constructed in sections, but the ay is to wind the wires spirally in two continuous coils.

e rapid reversals of magnetisation which take place, quickly e iron core, however well it is laminated. This heat must and since n is enve- oy copper, t must be l to the before it h the ex- ir. This f the con- s very un- . and for several ons it is preferable to place the iron outside instead of wire, the position of the iron being quite immaterial, t can act effectively in leading the lines of force through l paths.

FIG. 233.



233 is illustrated one method of constructing such a r. Its external appearance is that of a massive ring of nal diameter, and in the figure is shown a section taken liameter, at right angles to the plane of the ring. The d secondary coils are each wound in a single coil, and ether concentrically. They are wrapped round with an material, and over this is wound spirally an enormous soft iron wire. The inner coil of thick wire, S S, is the

secondary, while the primary coil of thinner wire, P, P, lies
it, and it will be observed that the depth of the layer of iron
about equal to the diameter of the compound coil of copp
Such a transformer gives fairly good results, for nearly
primary lines of force extend out to the massive iron shell
so doing cut the secondary. But it is an extremely tedious
expensive piece of apparatus to make on a large scale, on acc
of the slow process of winding the enormous length of iron
Further, if a fault should occur, and faults *will* occur, it bec
necessary to remove the whole of the iron wire before the
can be got at, to remove the fault.

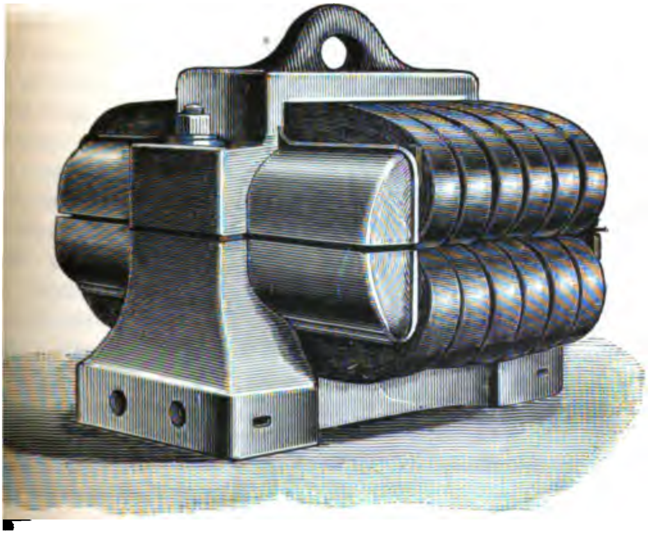
Consequently large transformers are not made in the
illustrated, although in most cases the principle is the
The apparatus usually consists of two coils of wire, nearly
in shape, lying side by side, with an easily fixed, and eas
movable laminated iron covering.

About thirty-three years ago a first-rate method of cons
a large transformer was patented by C. F. Varley, which
regarded as a combination of the two types mentioned. He
a bundle of iron wires of approximately equal lengths, an
this bundle wound the primary and secondary coils. These
were placed in the middle of the bundle, and extended
for a distance equal to one-third of its length, so that the iron
protruded from each end to a distance equal to the length
coil. The ends of the iron wires were then bent round
coils, so as to meet and overlap each other, thus compl
casing the coils with iron, except at one place through
connecting wires were led.

But the necessity for large transformers did not then
the method was scarcely at all employed. It is, howev
what extensively used at the present time, because of
with which the iron shell can be fixed or removed. The
practical development of this type is seen in the Fer
former, which is now doing heavy work in London. A
view of a Ferranti transformer, designed to receive abo
electrical horse-power at a high potential difference, an
large percentage thereof at a lower potential difference
fig. 234. A quantity of hoop-iron, divided into six b

base upon which the essential parts of the apparatus are built Over the middle of this is wound a layer of thick insulated or strip, to form the secondary coil. The finer wire to form primary coil is wound on a convenient frame in sections, :h are slipped over the secondary, and carefully insulated from ıd from the iron. The protruding ends of the hoop-iron lles are then bent over the coils, half at the top and half at ottom, as shown in the figure, their ends meeting and over-g for a short distance. The whole is then placed in a cast-amework, made in two pieces and securely bolted together, rtions of the coils not enveloped by the laminated iron overed, mainly for purposes of protection, by large shields, are cast with the frames.

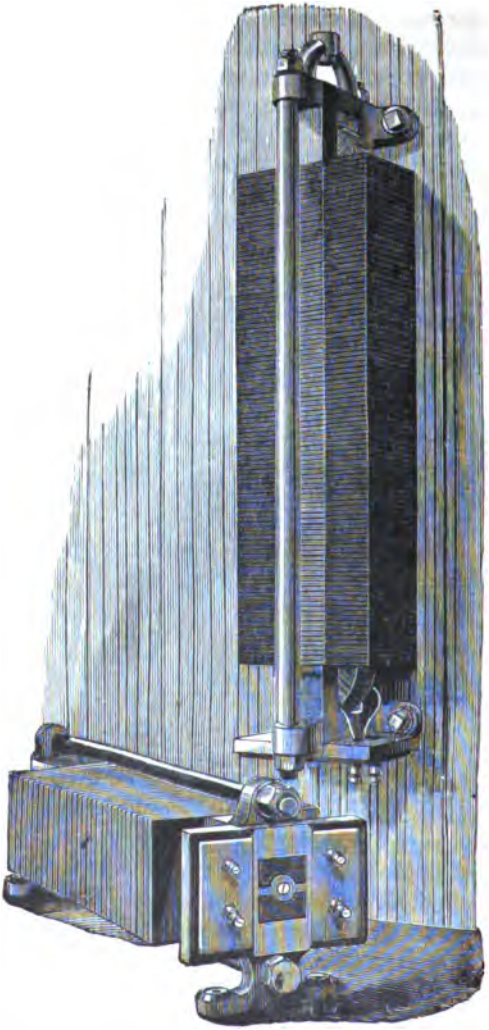
FIG. 234.



e lamination is, of course, not so effective as if iron wires mployed, or as if the iron bands were placed edge-on to the n of the lines of force ; but the construction is very easy, e spaces left between the bundles of hoop-iron greatly e the escape of the heat developed.

The magnetic circuit of many transformers is now built up of a number of flat plates of sheet-iron, placed so that the plane of the sheet shall be as far as possible parallel to the direction in which the lines of force are thrust through the iron. They are usually insulated by a thin coating of varnish, or by paper, or sometimes calico, and the devices by which such plates may be cheaply made and placed in position are very numerous. As they differ but little in principle, we need select only two patterns for description.

FIG. 235.



Two general views of the Mordey type of transformer are given in fig. 235. The thin iron plates are oblong stampings, and an oblong strip is stamped out of the middle of each, exactly equal in length to the breadth of the original plate. When this strip is placed across the middle of the plate its ends just reach to the edges thereof, leaving two rectangular openings, one on either side of the strip, which are subsequently occupied by the wire. The primary and secondary coils are wound separately on a frame of such a shape that each coil consists of two parallel straight portions, with rounded ends, the section being rectangular and of such size that the two coils when placed one over the other just fill the openings in the plates previously referred to. The larger stampings are slipped one by one over the coils, alternating with the narrower strips which are threaded through the coils, the coils, with the exception of their rounded ends, being in this way completely encased in iron. When the requisite number of plates have been placed in position, they are clamped tightly together between two cast-iron end-plates, held by bolts and nuts, as shown in the figure. The apparatus can either be fixed to the wall, suspended from the roof, or screwed down to the floor, as may be convenient.

There is a small air-space between the plates, whence the surface available for dissipation of heat is considerable.

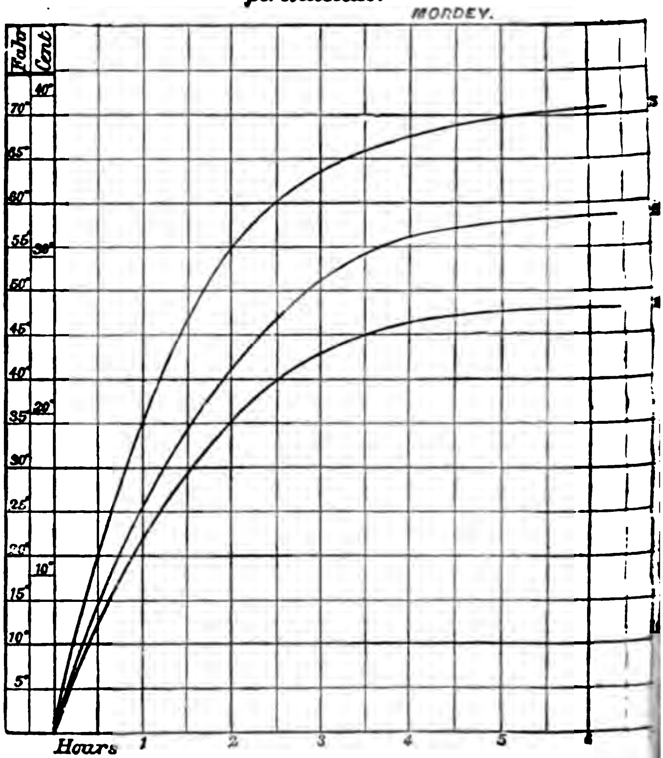
If a transformer is not well-designed or is improperly employed, the amount of power lost and appearing as heat may become a very serious matter. If the quantity of iron is so small that the magnetic induction through it becomes too high, then the loss by hysteresis is great; and a like result follows if the magnetisation is too rapidly reversed. Not only should the mass of iron employed be ample, but it should be so disposed that the cooling surface is also great; and if this latter point is attended to no difficulty should arise in working at an induction of about 7,000 C.G.S. lines.

Since in any case the loss due to hysteresis increases with the rapidity of reversal, it might be thought that the lower the rate of alternation employed the better. In practice the rate of alternation of the current supplied to transformers varies from about 50 to 130 complete alternations per second, and although the particular rate adopted *may* in every case be best suited to the particular apparatus, or to the conditions of working, there would certainly appear to be need for further inquiry into the matter.

Mr. Mordey has recently performed a lengthy series of ments to determine the rate of alternation best suited to his transformer, the method adopted being to discover at the least heat was developed in the apparatus. The rise in

FIG. 236.

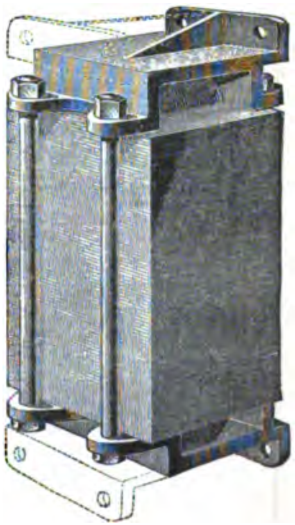
Rise of Temperature of Transformers at various periodicities.



perature was measured by means of a sensitive ther bulb of which was placed on the iron, and protected influence by a covering of cotton waste. A similar placed a short distance away, indicated the temper room, which, however, varied but slightly. Each ued for six and a half hours, the rate of alternation being kept istant during that time ; while the primary and secondary ential differences, and the load on the secondary circuit (con- ing of a number of incandescent lamps), were the same ughout.

The readings obtained during three tests are plotted in the e curves in fig. 236, and the result is somewhat surprising. lowest curve was that obtained with 100, and the middle one 125 alternations per second, the loss at the higher rate being iderably the greater. This is precisely what one would expect, it was found that the loss was still greater at the lowest rate, 75 alternations per second; and ighest curve represents the results ined with this rate. So that, evi- y, there is a best rate for every former, any increase or decrease ich would entail an increased loss wer by heat. For his own ap- as Mr. Mordey has decided upon lternations per second. There little doubt that these results are ughly reliable, for it is also the ence in practice that an abnor- se in temperature quickly occurs normal rate of alternation ns to be considerably increased uced.

FIG. 237.



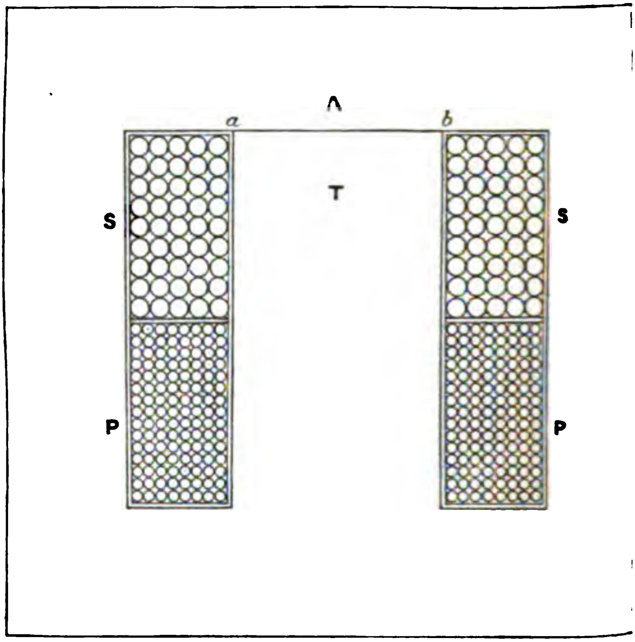
e explanation suggested by Dr. ng is probably correct, that, at te above the normal one, the principally due to hysteresis, while at lower rates more time for the eddy currents to penetrate deeper into the core waste more power.

fig. 237 is illustrated the transformer designed and con- d by Mr. J. G. Statter. A section is given in fig. 238.

iron stampings (fig. 238) are nearly square in shape, and long pieces are stamped out of each to form the spaces in the wire is placed. s s is the thick secondary coil, while

P P is the primary, and these two coils are wound to the proper shape on a suitable mould or frame, and placed one over the other as indicated in the figure. The strip T of each stamping is divided from the plate at one end, along the line *a b*. In building up the transformer the tongue T thus formed is bent at right angles to the plate, which can then be slipped over the coils, and the tongue bent back into its proper position. A large number of plates bei similarly slipped on, the wire is surrounded on all sides by iron.

FIG. 238.



Two strong cast-iron plates, and four bolts, hold the plat position, the plates forming a protective covering to the other exposed ends of the coils. They are also provided with fla and bolt-holes for fixing the transformer in any required posi The end-plates are frequently fitted with an extra flange indicated by the dotted lines, to which is screwed a wooden with a glass front, providing accommodation for a safety fuse, and also a double-pole switch, by means of which both wires leading to the primary coil can be simultaneously disconnected.

These transformers are made in a variety of sizes, but the most frequent are those capable of transforming down from 2,000 volts to 100 volts, 2,000 to 50, 1,000 to 100, and 1,000 to 50.

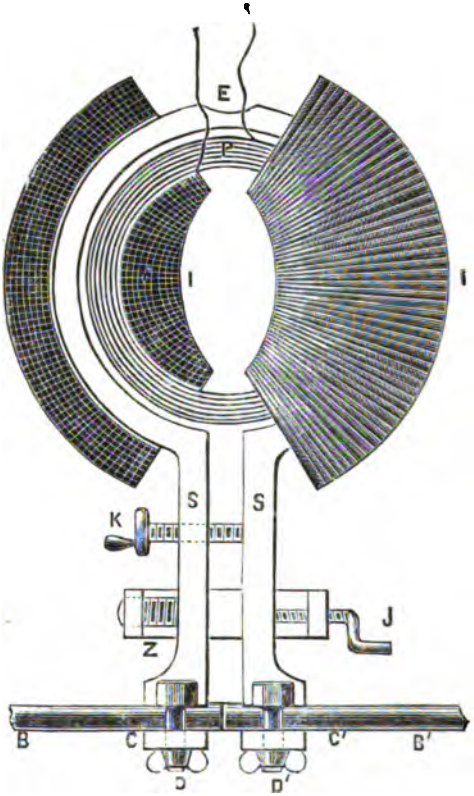
Transformers have been put to a novel and interesting use by Prof. Elihu Thomson, who employs them for the purpose of obtaining the very heavy currents, which are required in his method of electric welding. This method consists in placing the two pieces of metal required to be welded end to end, and subjecting them to moderate pressure against each other. A very heavy current is then passed through them, and as they make imperfect contact at their opposing surfaces, considerable resistance is there offered to the passage of the current, and a very intense heat is consequently developed at the point where it is required to make the weld. If the current is sufficiently strong, the opposing surfaces get white hot, and being pressed together they unite perfectly, bulging out, however, round the edges. It is necessary that the surfaces should be perfectly clean, and a flux, the composition of which depends upon the nature of the metals to be welded, is usually employed to prevent the oxidation of the surfaces and so render the weld more perfect. In the case of iron, a little borax is sprinkled over the ends of the rods.

But in order to sufficiently raise the temperature of thick rods of metal, enormous currents are required; for instance, a current of about 20,000 amperes would be required to weld a steel rod seven-eighths of an inch thick. It will readily be understood that in such a case the resistance of the current generator must be extremely small, otherwise the power absorbed in it would amount to many horse-power.

Secondary batteries might be employed for the smaller currents, but the most economical method is to generate an alternating current by means of a dynamo, at a fairly high E.M.F., and, reducing this to a lower E.M.F. by means of a transformer, obtain at the same time an increase in the current strength.

Various types of transformer have been employed for the purpose, one form being illustrated by the diagram in fig. 239. The primary coil, P, is composed of a number of turns of wire, wound in a circular coil; the secondary consists of a single massive copper strip, S S, bent into a circular form, and placed concentrically with the primary coil. Over the two coils is wound a quant of iron wire, I I, in two masses, space being left between the on one side, for the passage of the wi leading to the p mary coil, and on the other side, to br out the mass straight bars form the ends of the p mary coil. The b can be held ope means of the sc at K; their extre ties being provi with massive cla C C′, in which pieces to be wel B B′, are fixed spiral spring presses the ends gether, the pres being regulated means of the s at J.

FIG. 239.



For ordinary a current of 1 amperes is the mum required in such a case power is usually plied to the primary at an E.M.F. of about 600 volts, the current twenty amperes. A certain amount of this power is, of cour during the conversion; but a current of 12,000 amperes E.M.F. of nearly one volt can be obtained in the secondary

It is important to observe the reason for most of the heat being
reloped at the proper point. When the current is started in the
ondary circuit, the resistance at the junction is far greater than
resistance of the whole of the remainder of the circuit ; con-
uently the fall of potential there is comparatively very great,
t is, nearly the whole of the power appearing in the secondary
xpended in overcoming the resistance at the opposing surfaces.
se surfaces get hot, and being pressed together, they then make
h better contact. The rise in temperature, however, consider-
increases the resistance, and consequently the expenditure of
er at this point is still proportionally great. The ease with
h the heat can be confined to any particular locality consti-
one great advantage of the method. It is usual to quickly
ve the welded pieces, and hammer the joint into shape on an
. The clamps make contact with a large surface, to avoid, as far
ssible, the introduction of resistance, and they are so designed
the removal of the welded rods can be speedily effected.

he voltmeter illustrated in fig. 106 was specially constructed
se with one of these transformers, the potential difference in
econdary circuit ranging up to about 2·5 volts.

here are two distinct methods of distributing power to a
er of transformers, each of which has several important ad-
ges to recommend it. First, the whole of the transformers
be joined in series, and a constant current sent through
hole of the primary coils. Secondly, they may all be con-
d in parallel between two main leads, which are kept at a
ant potential difference, so that the difference of potential
en the ends of all the primary coils is always the same.

he former is in some cases the more economical as regards
conductors, for the maximum current in them is only equal
t supplied to one transformer, and is the same when the
um amount of work is being done as it is during any smaller
d. But a generator is required which will supply a constant
ating) current, under all variations in the external circuit ;
s such a machine does not at present exist, it becomes
ary to employ somewhat unsatisfactory hand regulating de-
Difficulties also arise with regard to the regulation in the
lary circuit.

The E.M.F. appearing in the secondary circuit varies direct with the strength of the primary current. It also depends upon the number of convolutions in the two coils, and the goodness of the magnetic circuit (that is, upon the mutual induction between the two coils), and also upon the rate of alternation ; but as these quantities are usually fixed for any given transformer, we can say that the secondary E.M.F. varies simply with the current passing through the primary. The strength of the secondary current, how-ever, will depend largely upon the resistance of the secondary circuit. Now in the case of a series transformer the primary current is kept constant, therefore the secondary E.M.F. is also con-stant, and manifestly we cannot maintain a constant potential difference at the secondary terminals, nor a constant secondary current, if the secondary resistance is in any way varied. Were the lamps joined up in parallel it would be necessary on cutting any one of them out to substitute an equal resistance, which would of course be wasteful.

The mutual induction might be, and in fact has been, varied to suit altering conditions by providing an adjustable core ; but this is also unsatisfactory.

A better plan is to join either arc or low-resistance incandesc lamps in series, and on removing one to replace it by a resistan coil, or, preferably, by a choking coil, that is to say, by a coil wire provided with an iron core, and having considerable self-in duction. Its apparent resistance should be equal to that of lamp which it replaces.

In such a series transformer the number of turns in the condary is, as a rule, equal to that in the primary, through wh a current of 10 amperes is maintained.

But if the transformers are joined up in parallel, and a c stant (alternating) potential difference is maintained betwee mains across which their primary coils are connected, then almost constant potential difference can be obtained in the seco ary circuit, even though the resistance therein be consider varied. The lamps can be joined in parallel, and if the transfo is properly designed it will be almost self-regulating ; for the cu passing through the primary, and therefore also the secon E.M.F., will be almost proportional to the number of lamps th in circuit, that is, inversely proportional to the secondary resistance.

The reactions which cause this self-regulation are very important and interesting, and in order to better understand them the student may, with advantage, again read some of the remarks concerning self-induction, &c., in Chapter VII.

On considering the construction of either of the parallel transformers just described, it will be apparent that since the primary coil consists of many convolutions, and is almost completely surrounded by a mass of soft iron, the conditions for enormous self-induction exist. In fact, supposing the secondary circuit for the moment to be absent, or disconnected, the self-induction is so great that an appreciable interval of time elapses, before a current in the primary rises to its full value, although the potential difference may be high. And if the potential difference be rapidly alternated, it will not remain constant in one direction long enough to allow any sensible current to be forced through the coil. But supposing the secondary circuit is completed through a rather low resistance, so that it is possible for fairly strong currents to flow therein, then the conditions are altered. For directly a current *commences* to flow in the primary coil, the lines of force springing out from the wire, not only cut the neighbouring convolutions of that coil tending to give the effect known as self-induction, but also cut, and set up an opposite current in the secondary. The lines of force due to this secondary current re-act on the primary coil (see fig. 116) in just the opposite sense to its own lines of force, tending thereby to neutralise the self-inductive effect, and allowing the primary current to rise rapidly. Although the length of the secondary is less than that of the primary, the current flowing through it is much greater, which may be expressed by saying that the lines of force per unit of length are more numerous. Consequently, if the secondary resistance is very low, allowing strong currents to flow, this reaction is competent to reduce the apparent primary self-induction to a very small value.

If then a number of lamps are joined in parallel in the secondary circuit, an increase in the number switched in means an increase in the secondary current, and a corresponding increase in its reaction on the primary, which allows a greater current strength to be attained therein. While when all the lamps are cut out, the primary self-induction is sufficient to throttle or choke back the current almost entirely. On account of these splendid self-regulating properties, nearly all distribution is performed by means of transformers joined in parallel. Although the size of the mains is somewhat larger than on the other system, the advantages far more than counterbalance this objection, and it is a comparatively easy matter to obtain an alternating generator which can maintain a constant potential.

By regarding the action of the primary upon the secondary coil in the manner developed in Chapter VII., it will be at once apparent that the currents in the two coils are always in opposite phase; in fact, in an ordinary transformer, the secondary negative maximum occurs almost simultaneously with the primary positive maximum and *vice versâ*.

In all cases great care must be taken to avoid a leakage from the primary to the secondary circuit, for a potential difference of several thousand volts, such as is frequently employed, might cause a fatal accident in the actual lamp circuit should any other point in the primary circuit be making earth at the same time. Many safety devices have been suggested, one being the interposition of an earth-connected metal sheathing between the two coils; so that any breakdown in the insulation would cause a sufficiently strong current to flow to earth, to melt a safety fuse in the primary, and thus disconnect that particular transformer without interfering with others working in parallel with it.

Such a fuse would also act if by any means the apparatus got short-circuited; and something of the kind is essential, for otherwise not only would all the transformers be deprived of power, but the heavy current which would result might cause serious damage.

The metal sheathing referred to should be insulated with extreme care, and must not form a closed metallic circuit round the inner coil, otherwise powerful eddy currents would be induced in it.

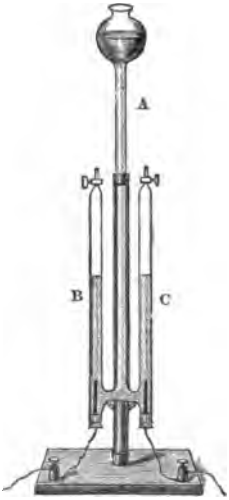
Another safety device is due to Major Cardew. Between two horizontal stout brass plates is placed a strip of aluminium foil, one end of which is free while the other is attached to the lower brass plate, which is in its turn connected to earth. The upper plate is connected to the secondary coil, so that should this plate assume a much higher potential than the earth, the foil would be raised by electrostatic attraction, and, touching the upper plate, would short-circuit the secondary coil. This would allow a sufficiently strong current to pass through the primary to melt a fuse placed in the circuit, and in that way cut out the transformer. If the primary circuit is making earth at any point, and any leakage occurs between the primary and the secondary, the upper brass plate is immediately raised to a sufficiently high potential to attract the foil, and cut out the transformer in the manner described.

CHAPTER XIV.

SECONDARY BATTERIES.

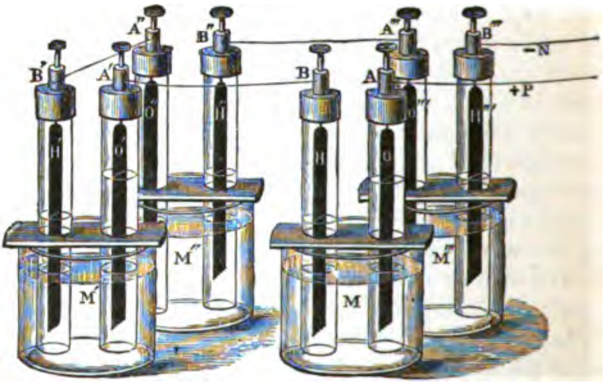
It was stated when describing the simple cell, that its great drawback, so far as concerned its general utility, was its comparatively rapid polarisation, a phenomenon which consisted in, or rather resulted from, the development of a film of hydrogen gas upon the surface of the negative plate. This hydrogen being electro-positive to zinc, having, that is to say, a higher potential than zinc, a counter electro-motive force was set up, and the conditions for the flow of a counter current thereby determined. But chemical reactions, similar to those which take place inside a battery cell, may be repeated in any part of the circuit by causing the current to pass through suitably arranged metals and liquids. The usual method of performing electro-chemical experiments is to place the ends of the wires connected to the poles of the battery in a vessel containing the liquid upon which the current is to act. Thus, if the ends of two copper wires terminating in copper plates, are connected to the copper and zinc poles respectively of the battery, and placed in a vessel containing acidulated water, then the passage of a current will cause a quantity of that water to be decomposed, and the constituent gases, oxygen and hydrogen, to be released from their state of combination. The hydrogen will accumulate on the surface of the plate connected with the zinc pole, while the oxygen will combine with the other plate, just as it happened with the zinc plate in the simple cell. If, however, we substitute a strip of platinum for the copper plate connected with the copper pole of the battery, the liberated oxygen will not enter into any combination, but remain in a gaseous state, a large portion of it rising into the air, and the remainder adhering to the surface of the platinum or entering its pores and becoming in a measure occluded or absorbed by it. The absence of chemical combination between the platinum and oxygen is due to the weak chemical affinity subsisting between those two simple bodies. By observing proper precautions the two gases may be collected separately, the apparatus for the purpose of producing the decomposition and collecting the products being called a voltameter. Fig. 240 is an illustration of a serviceable form of this class of instrument. There are three glass tubes, all in communication at their lower extremities, the middle one, A, being taller than the others and terminating at the top in a small reservoir, to keep the two outer tubes, B C, supplied with solution, and to prevent the liquid overflowing when driven from B and C. Platinum wires are fused through the glass and terminate inside in strips of platinum foil, their outer extremities being connected to terminals fixed on the wooden base. Taps are ground into the upper portions of the tubes B, C, affording facilities for the escape, when required, of the confined gases. On sending a current through the solution, the decomposition of the water takes place, the oxygen collecting in one tube and the hydrogen in the other, according to the direction of the current. The graduations on the tubes show readily that the quantity of hydrogen evolved is always twice that of the oxygen, in consequence of the fact that the gases exist in that proportion when combined to form water.

FIG. 240.



If the platinum electrodes are now disconnected from the battery and joined up to a galvanometer, it will be seen that a current of electricity is produced by the voltameter, but that the direction of this counter or secondary current is opposite to that of the battery or primary current which caused the separation of the gases. A series of four voltameters constructed for this purpose, and known as Grove's gas battery, is shown in fig. 241. Each cell consists of two tubes, A B, closed at the top and dipping into a glass vessel, M. A platinum wire is fused into the upper portion of each tube, and carries a long strip of platinum foil. Assuming the current from the battery to enter the series by the wire P and leave by the wire N, oxygen will be collected on the electrodes O, O′, O″, and O‴, while hydrogen will be collected on H, H′, H″, and H‴. If, after the current has been allowed to flow for some little time, the terminals A and B‴ are connected to a galvanometer, a current will be observed to flow, opposite in direction to the charging or primary current, that is, from A through the galvanometer to B‴; and this reverse or *secondary* current, which is, after all, only the effect hitherto referred to as polarisation, taking place under favourable circumstances, will continue to flow so long

FIG. 241.



as the gases remain in contact with the platinum. As a matter of fact, we have set up a secondary battery with 'plates' of hydrogen and oxygen, and in maintaining the current, the hydrogen in the tubes B combines with oxygen of the water forming new water molecules, while the equivalent hydrogen eventually released from the water combines with the oxygen in the tubes A. This action results, therefore, in the formation of water, as shown by the very simple equation :—

$$H_2+OH_2+O=OH_2+OH_2=2OH_2.$$

We see here, then, an exact counterpart of the action that takes place in a primary cell, resulting there in the polarisation of the cell and the tendency to generate so-called secondary currents.

The difference of potential or electro-motive force between the free hydrogen and oxygen is 1·47 volts, and that is a measure of the force of chemical combination between these gases, whence it follows that, in order to overcome this force of combination, and therefore to decompose the water, we must employ for each secondary cell a primary current whose electro-motive force exceeds 1·47 volts.

Cells in which the energy of chemical change can be thus stored up, to be given out again when required in the form of an electric current, are frequently called electrical accumulators or electrical storage cells. It is not, however, electricity which is stored or accumulated, but rather a quantity of the active constituents of a cell, and it is the subsequent chemical action between these constituents which causes the flow of electricity. It is therefore preferable to style them secondary cells. This will be more apparent when it is remembered that a primary cell can have a current sent through it in the opposite direction to that in which the current generated by it would flow, and this current will cause the usual negative plate to be more or less dissolved and the positive plate replenished, setting up the conditions necessary to the re-establishment of a primary current. If, for example, we suppose a powerful reverse current to be urged through a Daniell cell in which the copper sulphate has been exhausted, the copper plate will be partially dissolved and copper sulphate reformed, while zinc will be deposited upon what remains of the zinc plate. The cell is then able to again generate a current of its own.

Although the water cell is exceedingly interesting, as a secondary generator it is not a practical piece of apparatus, for it is only able to maintain a current for a very short space of time.

Many experiments have therefore been performed to determine the best liquid and electrodes (the metal plates immersed in the liquid), for a practical form of secondary battery. The most assiduous worker in this field was Planté, and the result of his labours was the discovery that lead electrodes in a solution of sulphuric acid give the best results. He found that a large portion of the oxygen combined with the plate at which it was released, forming an insoluble compound, which when opposed to a clean metallic lead plate developed a potential difference of from

2 to 2·5 volts. In Planté's method the lead plates employed were comparatively very large with a view to increasing the amount of active material and reducing as far as possible the resistance of the cell. They were first laid one over the other, but separated by strips of non-conducting material, and then rolled up together in a kind of double spiral. In this way an enormous surface was presented to the liquid. On sending a primary battery current through the cell, from plate to plate, the water was decomposed, the oxygen combining with the metal at the positive electrode to form peroxide of lead, PbO_2, while the hydrogen was precipitated upon the negative electrode in the gaseous form, without in any way attacking the metal. The cell so acted upon became a secondary cell in which the negative electrode acted as the positive plate, being a sheet of lead with a more or less complete film of gaseous hydrogen, the other plate or positive electrode with its film of insoluble lead peroxide behaving as the negative plate. It will thus be seen that the pole of the secondary which is connected to the positive pole of the primary generator, whether a battery or a dynamo machine, becomes the positive pole of the secondary, the other extremity becoming perforce the negative pole.

On permitting the reverse or secondary current to flow, what remained of the hydrogen was oxidised and converted into water, some of the subjacent lead being also oxidised at the expense of the water. On the other hand, the peroxide on the other plate was deoxidised or reduced to metallic lead in a 'spongy' form. These experiments can be very easily performed by sending for a short time a current from three or four good-sized Daniell cells through a vessel containing two pieces of sheet lead immersed in sulphuric acid solution. The piece connected to the copper pole of the battery will, after the passage of the current, be discoloured, and assume a brownish tint, owing to the partial oxidation of the surface of the metal. The amount of chemical change taking place during these reactions is, however, very small, too small to answer any practical purpose, and this is due in a great measure to the comparatively small amount of surface exposed, and to the fact that the greater part of the hydrogen escapes instead of adhering to the plate.

The next step taken by Planté in the development of the modern form of secondary cell was an important one, and that was the adoption of a method for increasing the available surface of the metal electrodes. It was found that after sending the primary current through the secondary cell for some time, and so nearly covering the surface of the positive electrode with a film of the peroxide, the oxygen released from the water, instead of combining with the lead, formed into bubbles and escaped into the air. There was thus for a given metallic surface a limit to the amount of peroxide that could be formed.

The current was consequently reversed, that is to say, the cell was allowed to discharge itself almost completely, so that the spongy lead plate became oxidised, and the other deoxidised and reduced in its turn to the condition of spongy lead, with a proportionally increased surface. A fresh direct or charging current on being sent through the cell again oxidised this extended lead surface and reduced once more the negative surface to the spongy lead state. These reversing operations being continued for some time, both positive and negative surfaces were eventually very considerably increased and rendered more or less porous, one of them being always in a state of oxidation. After a few days, however, a period of rest was allowed between the reversals with a remarkable and most useful effect due to local action. The lead peroxide did not form a continuous impervious coating over the plate, but allowed the solution to pass between its particles and come into contact with the metallic lead. The peroxide being at places in direct contact with the lead, a simple voltaic pair was thus established with the lead for the positive and peroxide for the negative elements. The acid attacked the lead and formed lead sulphate ($PbSO_4$), which is, however, but a poor conductor of electricity; this sulphate became available for the subsequent electrolytic action. The amount of lead actually affected or made active was thus considerably increased and the porosity of the plate gradually made more and more complete. The process of 'forming' the plates might have been continued until the whole became porous by its conversion into spongy lead, but there is a practical limit to the action, for if pursued too far, the plate would fall to pieces simply on account of its inability to mechanically support itself.

The cell being once formed, no further reversal takes place excepting for the purpose of discharging it to perform useful work.

This method of forming the plate is, however, very tedious and very expensive, and many efforts have been made to overcome the objection. One method is to subject the lead to a nitro-sulphuric acid solution which rapidly eats into the metal and increases its surface correspondingly. Another method is to fill a vessel with molten lead, and, as it is on the point of solidification, to make an opening in the bottom, and allow such of the metal as remains in the liquid state to flow out, leaving behind it a spongy porous mass. This is cut up into plates of the required dimensions.

Lead plates pure and simple, often known as Planté plates, are now only occasionally used, the cell more generally employed being that based upon the idea of Faure, which was to coat the plates with a paste of lead oxide, and so to more easily extend the lead surface. A mixture of sulphuric acid and minium or red lead (Pb_3O_4) was made, which resulted in the formation of lead sulphate ($PbSO_4$). This was applied to both the positive and negative plates, that on the plate in connection with the positive pole of the primary battery being by the current converted into peroxide of lead, by the absorption of oxygen, while the paste on the other plate was reduced more or less to the condition of spongy lead. It will thus be seen that the great value of Faure's invention is to minimise the amount of energy required to be expended in 'forming' the plates.

It is now the practice to use a paste of litharge (PbO) and acid for the plate connected to the negative pole, although makers vary the pastes considerably. In some cases minium only is employed. In others a mixture of litharge and lead sulphate; and in others, again, all three substances, viz. minium, litharge, and lead sulphate enter into the constitution of the paste. In all cases, however, the ultimate result of the initial charging current is the same, viz. the conversion of the paste on the positive plate into peroxide, and of the paste on the negative plate into spongy lead. Assuming the plates to be in the state of lead sulphate and lead monoxide (or litharge) respectively, the initial action may be summarised by the equation :—

$$\underset{\substack{\text{Lead}\\\text{sulphate.}}}{PbSO_4} + \underset{\text{Water.}}{2OH_2} + \underset{\substack{\text{Lead}\\\text{monoxide.}}}{PbO} = \underset{\substack{\text{Lead}\\\text{peroxide.}}}{PbO_2} + \underset{\substack{\text{Sulphuric}\\\text{acid.}}}{SO_4H_2} + \underset{\text{Water.}}{OH_2} + \underset{\text{Lead.}}{Pb}$$

It will be seen in this case that the positive plate exchanges its SO_4 for two atoms of oxygen, that the negative plate loses its oxygen, and that one of the water molecules is converted into sulphuric acid, so that the quantity of acid in the solution gradually increases, while the quantity of water as steadily diminishes.

The secondary current, during the process of discharge, reverses this state of affairs, the two plates being converted into lead sulphate. The process is doubtless brought about in several stages, but they may be represented by the following equations :—

$$PbO_2 + 2SO_4H_2 + Pb = PbO + SO_4H_2 + OH_2 + PbSO_4.$$

The lead monoxide then reacts with the sulphuric acid and forms lead sulphate and water thus :—

$$PbO + SO_4H_2 = PbSO_4 + OH_2.$$

Or combining the two equations :—

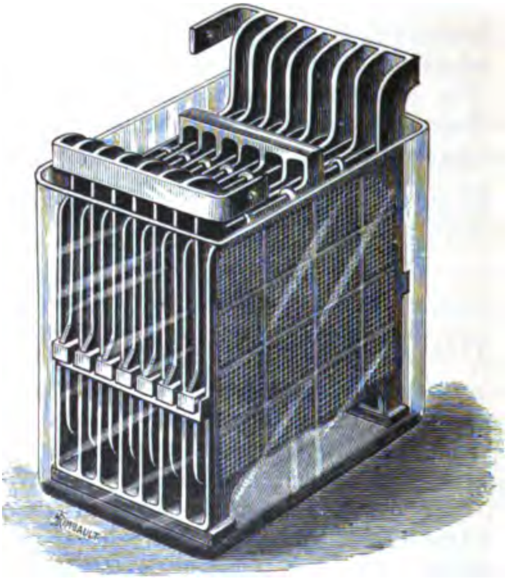
$$PbO_2 + 2SO_4H_2 + Pb = 2PbSO_4 + 2OH_2.$$

These reactions, however, affect only a small portion of the plates ; that is to say, the active portion of the cell is far less than that which remains passive.

The pastes, one and all, adhere very feebly to the lead plate, and many devices have been attempted to secure better adhesion. One of the earliest plans was to score or scratch the lead surface. Then it was indented, the indentations developing subsequently into perforations. The paste, on being squeezed into the holes, certainly kept its position much better than when simply smeared over the surface of the lead, but the quantity of paste exposed to the liquid was reduced. Eventually, leaden grids were cast containing sufficient metal to bear the weight of the plate, the holes being square and somewhat pyramidal, that is, smaller in the middle of the plate than on the surfaces, so as to prevent, as far as possible, the peroxide from falling out. An illustration of the latest type of cell, manufactured by the Electrical Power Storage Co., is given in fig. 242. A number of grids of lead, or of a hard lead alloy (lead mixed with a small proportion of antimony), are filled with the paste, the number varying with the size of the cell, but always with one negative plate in excess of the number of positive plates.

The cells are usually provided with 15 or 23 plates, of which 7 and 11 respectively are intended for the positive, and the remainder for the negative surface. The object of having a large number of plates, is, of course, to increase the capacity of the cell, and to reduce its internal resistance without resorting to the use of inconveniently large plates. Each grid measures about $8\frac{1}{2} \times 9\frac{1}{2}$ inches, and is $\frac{3}{16}$ inch thick, the weight being about 5 lbs.

FIG. 242.



The lead grids are provided with lugs for the purpose of connection, the lugs of the positive plates being all melted or cast on to one leaden strip or band, the lugs of the negative plates being similarly secured to another strip. The plates are placed in the cell alternately, the distance between two adjacent plates being about a quarter of an inch, which is sufficient to allow pieces of the plates or paste that may become detached to fall to the bottom of the cell. Bent strips or forks of ebonite, celluloid, or other suitable material are placed between the plates to keep them apart and prevent internal contact. The negative plates in each cell are also held rigidly together by means of two stout strips of lead melted on to solid extensions from the lower edges, two others being also secured to the sides of the plates about half-way up. These connecting strips, one of which is shown at the left-hand side of the figure, serve as a further means of keeping the negative plates in position. The bottom strips rest on slabs or strips of paraffined or varnished wood so as to support them at a height of about 1½ inch above the bottom of the containing cell, affording thereby plenty of room for any scales or pellets that may fall to the bottom to lie clear of the plates. Lugs cast on to the sides of the positive plates rest in small ebonite shoes, which are supported by the side-strips of lead attached to the negative plates. The positives are also connected together across the top by the substantial lead strip shown a little to the right of the middle of the upper edges of the plates. The connecting strip to be seen on the left is melted on to projections from the corners of the plates, consequently they can be readily lifted out of the cell, without necessitating the removal of the negative plates. The containing vessels are best made of stout glass, an opportunity being thus afforded for the proper inspection of the cell without taking it to pieces or removing the plates. The upper portion of the outer surface of the glass vessel should be coated with wax, vaseline, or some such material, to prevent 'creeping' and escape of the current by way of the moisture that would otherwise condense over the whole of the external surface. To further ensure good insulation, the cell should be placed on a varnished wooden tray or on two triangular pieces of wood supported by insulators of the so-called mushroom pattern illustrated in fig. 243. A sectional view of the insulator is also given in fig. 244. The channel in the lower cup contains a quantity of resin oil or of some other non-evaporating oil, in which the upper cup, coated with shellac varnish, rests. Sometimes, however, the cells are simply supported on shelving made of three or four strips of triangular wood. The cells should not be quite in contact, but tolerably close together, and the connections made by clamping the lead strips of adjacent cells firmly together—the positive pole of one cell to the negative of the next, and so on. The positive poles should be painted red for the purpose of distinction. All leading wires should be as short and of as low resistance as possible, so as to avoid unnecessary waste of energy in overcoming the resistance of the connections.

FIG. 243.

FIG. 244.

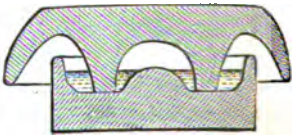
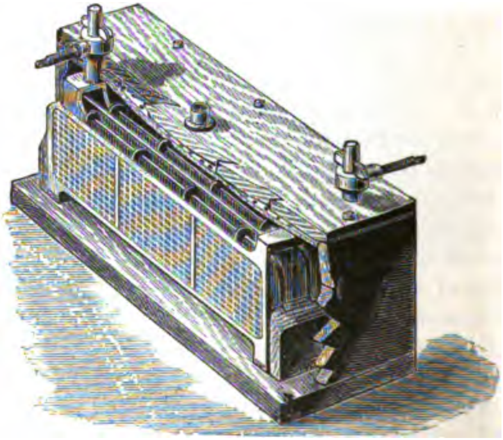


Fig. 245 illustrates a very useful form of cell specially constructed for train lighting. It is enclosed, like other classes of cells intended for ship lighting, carriage lighting, &c., in a teak box, and contains, to suit different requirements, either nine or fifteen plates separated by celluloid forks. Sometimes, in order to further avoid the risk of contact and short-circuiting between adjacent

FIG. 245.



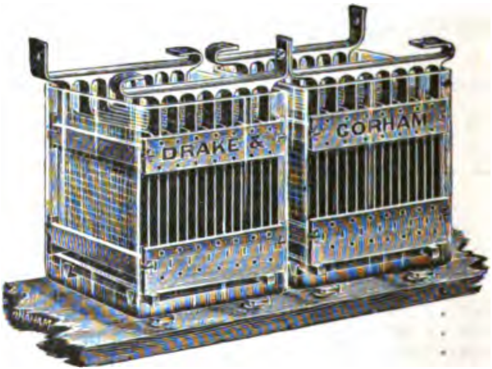
plates, thin perforated celluloid sheets are interposed between them. Connection between adjacent cells is of course made externally, rods attached to the connecting strips passing through the covers for the purpose. Connecting rings fit on to these rods, through slots in which wedges are driven to secure good electrical contact, the rings being joined together by stout wires or rods, as indicated in the figure. Cells are also made specially for tramcar driving, these being constructed as light as they practically can be, and enclosed in teak or ebonite boxes. They are made in four different sizes containing as many different numbers of plates.

A few details concerning some of these various types of cells will doubtless prove of service. In the subjoined table, L indicates cells intended for general, C for railway carriage, and T for tramcar lighting.

DESCRIPTION OF CELL		Acid 1·170 sp. g. for each Cell	WORKING RATE		CAPACITY	APPROXIMATE EXTERNAL DIMENSIONS				Weight of Cell complete with acid
No. of Plates	Material of Box		Charge Amperes	Discharge Amperes	Ampere-Hours	Length	Width	Height	Height over all	
		lbs.				ins.	ins.	ins.	ins.	lbs.
L 15	Teak .	35	25 to 30	1 to 30	330	9⅛	13	17⅛	19⅛	143
	Glass .	47	25 „ 30	1 „ 30	330	9⅝	11¼	13¼	15¾	128
L 23	Teak .	53	38 „ 46	1 „ 46	500	14¾	13	17⅛	19⅛	228
	Glass .	67	38 „ 46	1 „ 46	500	14	11¼	13⅜	15⅞	211
C 9	Teak .	8·4	6 „ 8	1 „ 8	72	6	13⅛	6¼	7⅛	38
C 15	Teak .	14	12 „ 14	1 „ 14	136	9½	13⅛	6¼	7⅛	62
T 15	Teak .	14	24 „ 28	1 „ 30	95	8¾	8¾	11⅛	13⅜	53
	Ebonite	14	24 „ 28	1 „ 30	95	8	7⅝	11	12¾	42
T 23	Teak .	22	38 „ 42	1 „ 50	145	13¼	8¾	11⅛	13⅜	80
	Ebonite	22	38 „ 42	1 „ 50	145	12¼	7⅝	11	12¾	66

Messrs. Elwell Parker also manufacture a very useful form of secondary cell, the main principles of which, however, are similar to those involved in the construction of the cell just described. Two of these cells are shown in fig. 246. The distinguishing features consist in the construction of the grids, and the method of supporting the plates. The grids are made of an alloy which is said to be considerably stronger than the material formerly employed, and to be practically inoxidisable in the sulphuric acid solution. The holes in the grids are 'burred' over, by a process patented by Messrs. Drake and Gorham, so as to form 'lips,' which assist in keeping the pellets of oxide in their places. The plates are ingeniously supported and kept in position by means of round projections which fit into parallel rows of holes perforated in slabs of ebonite, as shown in the figure. This is a detail, but it is a feature of some importance. In an earlier form of cell, the leaden pins were all in one line, so that should any conducting material fall into the cell it might drop across them and cause short-circuiting. To effectually prevent contact between adjacent plates, small ebonite 'forks' are placed between them, and the set of plates is supported on blocks of paraffined wood to keep them clear of the bottom of the cell.

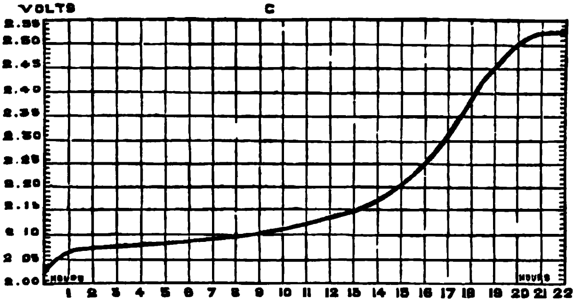
FIG. 246.



While it is essential that great care should be exercised in the manufacture of secondary cells, the treatment to which they are subjected is also a matter of great importance.

The charging current should be proportional to the number of plates, and, for the size of cell used for lighting purposes, should be equal to about 4 amperes per positive plate, so that the 15-plate cell requires 24 to 30 amperes. When the current exceeds this amount, it cannot increase the reduction of the sulphate of lead in proportion to the extra amount of current, and the surplus current is therefore wasted in the decomposition of water and the premature evolution of bubbles of oxygen gas from the positive surface, a phenomenon which is technically known as boiling. There is also a risk that the too-powerful current will cause bending or buckling of the plates, which, being very close together, stand a good chance of making contact one with the other, and so short-circuiting the cell. Precaution has also to be taken that the electro-motive force of the charging current should exceed that of the subsequent discharging current by about 10 per cent., or be at the rate of about 2·5 volts per cell, being, however, a little lower at starting than when approaching the completion of the charge. The charging should be continued until the solution assumes a milky appearance, consequent on the evolution of free oxygen, the positive plates having then absorbed as much of the gas as they can take up. The E.M.F. of a secondary cell rises, although not uniformly, with the continuance of the charging current. In some important experiments, performed by Messrs. Drake and Gorham with a battery of 15 cells, a current of 22 amperes was employed, by which the E.M.F. was raised from 2·02 to 2·53 volts per cell. The variations in the rate of increase are shown in fig. 247, from which it will be seen that after 220 ampere-hours had been put in, that is to say, after a charging current of 22 amperes had been maintained for a period of 10 hours, the E.M.F. had risen gradually to 2·13 volts. After about 14 hours charging, when the E.M.F. was 2·17 volts, a somewhat sudden rise in E.M.F. was observed, which was continued until 2·53 volts were registered. The maximum E.M.F. usually obtained is 2·5 volts, at which point gases are freely evolved, and cause the milky appearance already referred to as boiling. It was for some years

FIG. 247.



considered to be very injurious to charge the battery to an E.M.F. exceeding about 2·25 volts per cell, it being thought that charging beyond this point, or overcharging as it was called, was responsible for the remarkable tendency of the plates to buckle or twist out of shape, and so to loosen and detach the pellets. This, it was supposed, was brought about by the freed oxygen destroying the grid. It has, however, been conclusively proved that overcharging is not only harmless, but actually beneficial. In the experiments previously referred to, some cells were charged without cessation in order to ascertain the exact amount of current necessary to destroy the grid. It was soon evident that the process was, at any rate, a slow one; but the experiment was continued, until the full prescribed current had been passed through, for more than two months. At the end of that time it was found that the lead conductor was practically as sound as before charging. The coating of fine peroxide formed on the surface was very thin; there was no sign whatever of buckling, and, further, the specific gravity of the solution, when the cells were left in their then fully charged condition, remained absolutely unaltered. The conclusion thence drawn was that the oxidisation of the grid caused by charging only penetrated to a very limited depth, and then ceased entirely, and that the coating of fine peroxide formed, actually protected the grid not only from deterioration by overcharging, but also from local action, hitherto supposed to be unavoidable. It was, then, established that the life of the grids was not proportional to the amount of charging, *i.e.*, to the number of ampere-hours put into a cell. We shall return to this question presently, but it is necessary now to enlarge upon the precautions to be adopted in the process of charging.

The solution, prior to charging, should be put in the cells to the height of about ½ an inch above the negative plates. It should contain about 20 per cent. of pure sulphuric acid, and have a specific gravity of 1·170 (that is, if a given volume of water weighs say 1 pound, the weight of an equal volume of the solution should be 1·170 pounds); but it will be seen from the equations already given that some of the water in the cell is changed to sulphuric acid, and causes the proportion of the latter to rise to about 25 per cent., increasing the specific gravity to about 1·220. This accretion of sulphuric acid, which is, however, lost on recharging the cell, raises the conductivity of the liquid about 10 per cent.

An instrument for measuring the specific gravity of the acid solution becomes, therefore, a necessity. Such a piece of apparatus is called a hydrometer, or, for this special case, an acidometer, a useful form being that shown in fig. 248, which is simply a glass tube weighted at the bottom with a quantity of small shot. The lower the specific gravity of the solution, that is to say, the lighter it becomes bulk for bulk, the deeper will the hydrometer be immersed. As the liquid increases in density the instrument becomes relatively lighter and therefore rises. Consequently, the scale on the tube can be made to indicate the relative density corresponding with the various depths to which the tube descends. Another very useful form is that known as Hicks' hydrometer (fig. 249), which consists of a flattened glass tube with the upper end bent over so as to allow it to hang on the edge of the glass containing-vessel, the tube being also perforated to facilitate the free circulation of the solution. Inside the tube are four small glass globules containing liquids of different specific gravities and different colours; each globule rises or falls at a distinct specific gravity, and allows thereby the condition or relative density of the solution to be very readily observed.

FIG. 248.

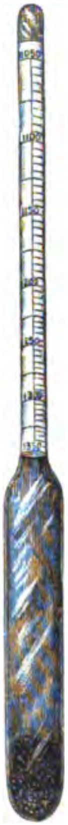
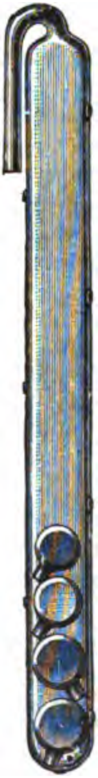


FIG. 249.

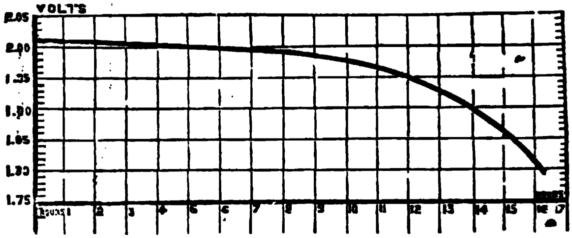


During the discharge the density of the solution falls until, when the cell is practically exhausted, it is only 1·150. The relative density of the solution thus affords an excellent means of ascertaining the condition of the cell.

The colour of the plates affords another good indication of their quality, the peroxidised positive plate being of a brownish or deep-reddish hue, and the negative or spongy lead plate being coloured grey or slate tint. There is thus a marked distinction in the colouration, which should always be discernible.

During the discharge the E.M.F. of the cells speedily falls to about two volts each, the higher initial electro-motive force being, no doubt, mainly due to the presence of hydrogen on the spongy lead plate. When this has been oxidised there remains the lead surface between which and the peroxide plate the electro-motive force falls very slowly to about 1·98 volt. The fall is then slightly faster, although after an output of 400 ampere-hours at the rate of 25 amperes, the total drop from the time that the cell settles down to steady work at 2·02 volts, is only about ten per cent. The rate at which the fall of E.M.F. takes place is clearly shown in the instructive curve given in fig. 250, determined experimentally by Messrs. Drake and Gorham.

FIG. 250.



The discharge was continued, however, until the E.M.F. was only 1·80 volt per cell, which is a point about 0·1 lower than it is practically advisable to go. With a fall to 1·90 volt the difference is only about 5 per cent.

In an experiment performed to ascertain the effect upon the plates of a rapid discharge a battery was divided into two halves, one of which (A) was repeatedly run out, but the other (B) was never discharged beyond the point at which the E.M.F. commenced to drop. The experiment extended over a considerable time, but gave the instructive result that when exactly the same number of ampere-hours had been taken out of each half, the plates of (A) showed signs of expansion or growing, whereas in those of (B) no change could be detected. The life of the grid was therefore proved to be dependent not on the *amount* of ampere-hours taken out, or on the work done, but on the treatment of the plates.

By the time the E.M.F. has dropped to 1·90 volt the greater portion of the surfaces will have resumed the condition of lead sulphate ($PbSO_4$), and there will then be considerable risk of the formation of a more obdurate form of sulphate, Pb_2SO_5, caused probably by the $PbSO_4$ combining with the monoxide. This hard white sulphate is very troublesome. It is insoluble, non-conducting, and very adhesive. When it falls off the plate it generally carries with it some of the active material, which is therefore wasted. It is consequently highly important that the E.M.F. of the cells should be tested periodically with a special low-reading voltmeter. Two or three of these instruments were described in Chapter VI.

The experiments further showed that buckling was almost invariably accompanied by the formation of the hard sulphate on the face of the plates, and that this enamelling could be prevented by charging, and was not due to impurities in the oxides or acid used; further, that when the plates were free from sulphate there was no tendency to buckle. In the case of the first use of cells, when the acid was first put in, the specific gravity dropped in spite of the charging, indicating the formation of sulphate; by persevering in charging the sulphate disappeared, and with it the tendency to buckle. It is, therefore, evident, as already stated, that in order to avoid buckling of the peroxide plates, cells on their first use (whether new or after long disuse) should be charged incessantly until they are considerably overcharged.

It has been ascertained that in almost every case where abnormal disintegration takes place the plugs of active material fall out of the plates in complete halves and in very hard condition; and analysis has shown that they contain an excess of sulphate, due to insufficient charging. On the other hand, in a few instances the active material has been found to have become disintegrated and fallen off in a fine powder, and this was specially observable when on account of a leak in the containing-vessel and consequent frequent addition of water, the solution had become extremely weak

In this case practically no sulphate was present, and the mass simply lost cohesiveness.

It would seem, then, that a certain proportion of sulphate in the material is necessary to bind together, but that excess must be avoided.

Buckling appears to be due to the expansion of the paste during sulphating, for lead, being a very ductile but non-elastic body, does not re-assume its proper shape when the subsequent partial contraction of the paste takes place, and to this must also be attributed the loosening of the pellets. The contraction being but partial, the positive plates become gradually increased in size with continued use.

The electrolytic effect of the oxygen upon the lead grid, slow as it is, is to render it more or less brittle, whence the bars crack and split, and the plate is then practically worn out. Owing to the stretching effect of the paste, it is necessary that the grid should be of equal strength throughout, and not made stronger in one direction than in another.

Mr. Reckenzaun has found that a positive plate which had when new a surface of 90 square inches, grew to 94·76 inches after one year's daily use, while others showed when almost worn out an increase from 90 to 97 square inches; these measurements being simply the product of the length into the breadth of the plate, and independent of corroded or oxidised furrows. The actual amount of surface in contact with the liquid is considerably greater than these figures would indicate, owing to the irregularities produced by the solution. The life of a positive plate is not, however, so brief as might be anticipated from the many little difficulties which beset it, for with fair and continuous usage its period of durability amounts to about three years. The decay of the plate is more rapid in the lower than in the upper half, owing probably to the greater density of the acid solution in that portion of the cell. The life of a negative plate, which is subject to but few of the troubles attending the positive plate, has been estimated at ten years, although it remains for time to demonstrate the truth or otherwise of this calculation.

A 15-plate cell is capable of yielding a current ranging from 1 ampere or less to about 30 amperes, or at the maximum rate of

4 amperes per positive plate. The discharging current may be even a little higher than the maximum used in charging. It should not, however, exceed it by more than about 10 per cent., otherwise the subsequent efficiency of the cell will, as already shown, be seriously imperilled. Of course, the total output cannot exceed or even equal the amount of energy put in.

When the rate of discharge is too great, there is considerable risk of causing unequal expansion of the plates, resulting sooner or later in buckling, loosening of the pellets, and short-circuiting. It is impossible to prevent a certain amount of the obdurate sulphate forming, and this being an insulator reduces the available active surface and increases the resistance of the cell. As already indicated, considerable difficulty is experienced in removing this sulphate, and under any circumstances a certain amount of disintegration of the peroxide is sure to ensue.

But experiments have been performed which tend to show that with a considerable increase in the charging E.M.F. the sulphate can be decomposed. Its formation can be to some extent prevented, by the addition of a small percentage of sodium sulphate (Na_2SO_4).

If the cells are discharged and then left to stand idle for any length of time, the sulphating takes place rapidly, and causes premature buckling.

The capacity of a cell may be defined as the amount of energy it is capable of storing, and is calculated generally in ampere-hours, that is to say, it is the product of the number of amperes at which the cell is able to discharge, into the number of hours through which it can maintain that discharge. Capacity is also estimated by the ratio between the weight of the material and the electrical output. Thus the ordinary form of cells yields about four ampere-hours per pound of plates complete, while, it is said, the best form of Planté cells only yields about one-half as much. The amount of surface exposed to the solution really determines the charge which a cell can receive, and is therefore a measure of its capacity.

The capacity of a cell is an important consideration, seeing that the prime cost is considerable, that the cell is bulky and therefore requires correspondingly ample accommodation, and that at present only a portion of the plate is utilised. The capacity can be increased by more thoroughly 'forming' the paste and reducing the metal in the grid, which we may call so much dead weight, but it is not safe to carry this reduction much farther than has already been done, or there will be considerable risk of the plate being unable to bear its own weight, and therefore of its falling to pieces. It is, however, possible that some more active pair than spongy lead and lead peroxide may yet be discovered.

Many attempts have been made to use other electrodes than lead for secondary cells, but with little success. Thus one was brought out in which there was a lead plate to be peroxidised, the other plate consisting of copper to be alternately dissolved and deposited from a copper sulphate solution; but the low electromotive force of this cell precluded its adoption. For somewhat similar reasons the adoption of other suggested solutions has been found to be impracticable, and there is therefore no need to further discuss them here.

The most prominent of recent productions is that of Mr. Fitzgerald, who makes use of a solid block of peroxide for the positive plate, dispensing altogether with the grid. He calls this substance 'lithanode,' and cells containing it have been proved to have considerable capacity, exceeding 5 ampere-hours per pound of plates.

There is also the possibility that some improvement in the method of treatment may yet be discovered, and this is, apparently, not such a very remote possibility, seeing that three or four years ago, it was the unanimous opinion that overcharging should be carefully guarded against, whereas now it is a well-established fact that no harm can possibly arise from so doing, beyond a wasting of energy, while beneficial results frequently accrue.

Coming now to the question of 'efficiency,' or the ratio of the energy taken out of the cells as compared with that put into them, it may be repeated that the former can never equal the latter. The phenomenon of boiling, for example, is an evidence of energy being wasted, for the current is then employed in the unproductive decomposition of water. It is often asserted that secondary cells are capable of giving out 80 or more per cent. of the charging energy, and this may be true with small cells wholly discharged, but the experience of those who have given the matter long and earnest attention is that the efficiency of cells of the ordinary sizes, discharged to their proper minimum E.M.F., ranges between 65 and 70 per cent. Even then great care has to be taken that the charging current is of the right strength and potential difference, and that the cells are maintained in the best possible condition. The efficiency of a cell depends very largely on the rate at which the energy is discharged, that is to say, it depends upon the current strength per unit of surface, or, as it is technically termed, upon the 'current-density.'

The highest safe rate, which has been already stated to be 4 amperes per positive plate, is equal to 0·01 ampere per square millimetre of surface, and an experiment with a small cell, quoted by Mr. W. H. Preece, shows how the efficiency varied with the rate of discharge or current-density thus :—

Current-density	Ampere-hours
0·013	44·6
0·048	30·5
0·090	30·2

It may be stated generally that the lower the density, the greater the efficiency, for with small cells slowly discharged, an efficiency or electrical return of upwards of 95 per cent. has been obtained. With a cell discharging at the rate of 5 amperes, an efficiency of 90 per cent. might be obtained, but on increasing the current to 40 amperes, the output falls to about 50 per cent., for when the rate of discharge is high, the E.M.F. is rapidly reduced. It is for this reason that with the 15-plate cell previously described, the discharge should not exceed 30 amperes, and if fully charged, such a battery can maintain this current for 10 hours, indicating a commercial capacity of 300 ampere-hours.

It remains now to consider the general utility and application of secondary cells. These features may be classed under three heads, viz. storage, regulation, and distribution.

As a means of storing energy to be afterwards converted into a current of electricity, the secondary battery stands alone. It is often compared to a domestic water cistern, but the analogy is not a very happy one, for the latter receives a periodical heav charge of water to be delivered in small or large quantities a required, while the former frequently receives its charge gradually or even intermittently as opportunity arises, whereas its rate of discharge often approaches the highest possible, and frequently exceeds the charging rate, when, of course, the duration of the discharge is considerably shorter than that of the charge.

No better illustration of the value of secondary cells as a means of storing electrical energy can be afforded than that referred to by Mr. Preece in a lecture before the Society of Arts. He said: 'On March 30 my gas-engine broke down. I quite forgot to give notice to the makers to send down men to repair it until six days had elapsed. It took five more days to repair the engine, so that for eleven days I had not been able to recharge the cells; but during all these days the light never failed, and we were not in any way inconvenienced. The useful capacity of my cells is 330 ampere-hours, and my nightly consumption is now about 30 ampere-hours. This was a very good test of the efficiency of the cells, for I obtained from them nearly all the energy they could usefully give. Only two cells were really exhausted during this time, but as I had two spare cells to replace them, their exhaustion did not cause me any inconvenience. The E.M.F. fell to 1·8 per cell, and the light in consequence was not so brilliant as usual. A good practical test of the efficiency of a battery like this is better than any isolated tests on single cells.' It will thus be seen that the use of a secondary battery reduces considerably the risk of a total stoppage resulting from the breakdown of the engine or other part of the machinery.

Secondary cells have also the advantage that, where they are used in sufficient numbers to maintain the ordinary number of lamps, they can, on emergency, be used to considerably increase the total amount of current supplied. For example, suppose the dynamo to be able to generate the same amount of current as the secondaries, the latter can be charged during the day, and both dynamo and battery employed independently for lighting purposes in the evening.

The battery is very useful as a regulator for maintaining a constant potential difference on a variable circuit which is being worked by a dynamo machine.

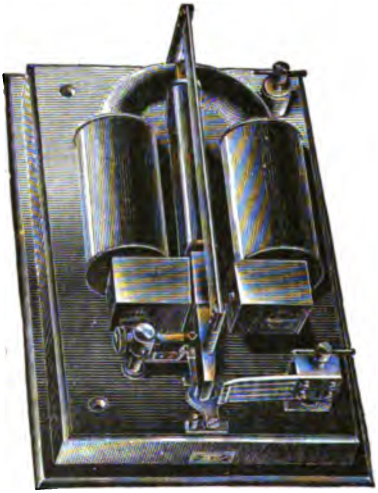
For such work, the battery is joined up across the terminals of the dynamo, which is constructed and driven so as to develop a slightly higher E.M.F. than the cells. Should the dynamo current, from any cause, fall in E.M.F. below that of the battery, an automatic switch cuts the dynamo out of circuit, and causes the circuit to be fed from the secondaries alone, with but little, if any, fall in the strength of the current. Conversely, should the dynamo E.M.F. become abnormally high, a comparatively strong current is urged through the cells, which form therefore a shunt to the main circuit and so keep the pressure practically uniform. Other applications of a somewhat similar character will be discussed when dealing with conductors.

There is another advantage pertaining to the use of secondary cells consequent on the fact that it frequently happens that the direct employment of an engine and dynamo for electric lighting purposes is inconvenient on account of noise, smell, &c. In such cases the current can be brought to the house by wire, and the energy there stored up for future use by means of secondary batteries, machinery of every kind being thus dispensed with.

The average electro-motive force of a secondary cell being two volts, and incandescent lamps, for the illumination of which they are mostly employed, being generally made to take a current with a potential difference of either 50 or 100 volts, it follows that, allowing a small margin for loss in the wires, switches, &c., 27 or 54 cells joined up in series will be required to maintain the necessary potential difference. The smaller battery of 27 cells would produce an electro-motive force of 54 volts, and assuming each cell to contain 15 plates and that the current strength is 28 amperes, the total output would be at the rate of $54 \times 28 = 1512$ watts, or, reckoning 746 watts to the horse-power, a trifle over two horse-power. A small portion of the electro-motive force would of course be absorbed in overcoming the resistance of the battery itself and its connections, the resistance of each cell during discharge being about 0·0012 ohm. The internal resistance, however, varies, as already stated, with the density of the solution and the condition of the plates.

An important piece of apparatus used in connection with secondary cells is the automatic switch, illustrated in fig. 251, which serves the function of automatically making and breaking the charging circuit at the correct moment, the circuit being closed soon after the E.M.F. of the dynamo exceeds the counter E.M.F. at the battery terminals by a predetermined amount, and broken as soon as the current falls to zero, the rupture of the circuit being accomplished without sparking. It consists of a horse-shoe electro-magnet fixed vertically and provided with large pole-pieces, approaching somewhat closely one to the other; a long central tongue oscillates between these pole-pieces, and has wound over it a coil of fine wire joined in parallel with similar fine wire coils on the outer legs of the magnet, and forming a shunt across the dynamo terminals. On starting the machine, the current passes through these coils, but when the E.M.F. rises to the required point, the tongue is attracted against the pull of a spiral spring, and, rubbing against the flat contact spring, closes the main circuit, which is completed through a few turns of thick wire on the limbs of the magnet, the direction of the current round the tongue and through the thick wire coils being such as to hold the tongue firmly over on the main-circuit spring. The thin-wire shunt coils round the magnet limbs are disconnected when the tongue is thus drawn over. On the cessation or failure of the main current, the spiral spring draws the tongue away from the main-circuit spring and, completing the shunt circuit, places the apparatus in readiness for charging immediately the E.M.F. rises to the required value.

FIG. 251.



Another useful piece of apparatus is an automatic alarum, the object of which is to indicate when an excessively high current is being drawn from the cells. In one of these alarums is a vertically fixed solenoid consisting of a few turns of thick wire, placed in the ain circuit. When the current exceeds a certain prescribed limit, he soft iron core is attracted, and a horizontal spring attached to it ompletes a local circuit, causing one of the cells to send a current hrough an ordinary electric trembling bell.

In addition to these, there are many other pieces of apparatus, ngenious in their way, and useful for special purposes, which we eed scarcely describe, although some of them will be referred to in the closing chapter.

CHAPTER XV.

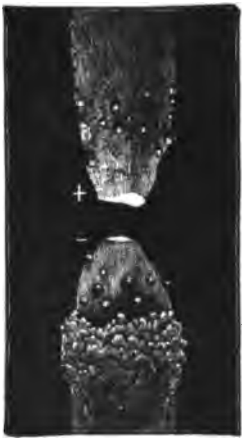
ARC LAMPS.

UNTIL within the last few years electric lighting was, except in the laboratory, only performed by the agency of the electric arc, a development of the classical experiment made by Davy in 1810, when he employed 2,000 primary cells of a very crude type, which he connected to two pieces of light wood charcoal about an inch long and one-sixth of an inch in diameter. When these 'were brought near each other, (within the thirtieth or fortieth part of an inch), a bright spark was produced, and more than half the volume of the charcoal became ignited to whiteness ; and, by withdrawing the points from each other a constant discharge took place through the heated air in a space equal at least to four inches, producing a most brilliant ascending arch of light, broad and conical in form in the middle.' When any substance was introduced into the arc produced by this battery 'it became incandescent : platinum melted like wax in the flame of a candle ; sapphire, magnesia, lime, and the most refractory substances were fused. Fragments of diamond and granite rapidly disappeared without undergoing any previous fusion.' The arched form taken by the luminous particles of carbon, resulted from the upward rush of the subjacent heated air. Were the carbons placed vertically, the particles would be disposed more symmetrically, and bear little or no resemblance to an arch. The term arch, in its abbreviated form, arc, is, however, retained as the name of the luminous space between the carbons.

The electric arc can be reproduced by placing in electrical contact two pieces of carbon, either of the gas-retort or of the prepared type, these forming the electrodes of a battery of twenty-five or more Grove or other cells of a similar E.M.F., and then drawing the carbons apart for a short distance. The electro-motive force of such a battery is altogether inadequate to cause a spark to dart across even the shortest air space. When, however, these rods are made to touch, a current is initiated, the particles in contact are immediately heated, and on separating the contact-surfaces, molecular disintegration and volatilisation take place and the air space is impregnated with so great a quantity of carbon particles raised by the current to a state of incandescence, that the resistance of the space is so far reduced as to allow the current to be maintained. The initiation of the arc is assisted by the momentary increase in the current due to self-induction in the circuit when the carbons are separated. The distance to which the carbons can be separated without absolutely disconnecting the circuit and so causing the arc to be broken, depends upon the E.M.F. of the battery, and can therefore, within certain limits, be increased by increasing the number of cells, or the potential difference at the dynamo terminals.

The maintenance of the ends of the carbon rods in a state of incandescence also involves a certain amount of consumption by ordinary combustion, some of the particles uniting chemically with the constituents of the atmosphere, although the products of combustion are very much smaller in quantity and far less harmful than those derived from a gas, oil, or candle flame. The two rods are not, however, consumed at equal rates, the consumption of the rod connected to the positive pole of the dynamo or battery, and called, therefore, the positive carbon, being approximately twice as much as that of the other or negative carbon; but this must not be taken as being invariably correct. One very interesting and important feature in connection with the electric arc is the difference of formation given to the carbon rods. The end of the positive rod becomes in a short time (see fig. 252) worn down to a somewhat conical form, the apex of the cone being, however, absent,

FIG. 252.



and the carbon hollowed out so as to form a kind of crater, and it is in the hollow of this crater that the most intense heat is developed, constituting it, therefore, the chief source of light. The negative rod is gradually consumed until its extremity is of a fairly true conical shape, but it is interesting to observe that some of the particles of which the positive rod is denuded are condensed upon the surface of the negative rod. When gas-retort carbon is used, the impurities fused give rise to small nodular growths which, under a lens or even a common magnifying glass, impart to the rods a remarkable appearance. These nodular excrescences do not manifest themselves when prepared carbons are employed. Their very presence denotes a wasteful consumption of energy, for they are, as it were, sorted out from the other constituents of the electrodes ; they are then concentrated and liquefied, and urged across the arc from one carbon to the other, without emitting that percentage of light rays which would arise, were the energy they absorb expended on the carbon.

In consequence of the unequal consumption and the remarkable difference in the ultimate formation of the extremities of the carbon rods, much of the light is really lost ; more especially is this so when, the carbons being placed vertically one over the other, the light is required in a horizontal direction on one side of the lamp. This loss can be partially avoided by placing the lower carbon a little out of line with the upper one, so that, instead of a crater being produced at the end of the upper or positive rod, the carbon is burned away in a more or less perfect curve on one side of the rod, the incandescent surface behaving to some extent as a reflector and projecting the light in a horizontal plane.

In some experiments performed at the South Foreland, it was found that, the intensity of luminosity in a horizontal direction from an arc established between two carbons placed vertically one over the other being taken at 100, the relative intensity when the lower end of the upper carbon was placed just behind the upper end of the lower one was—

In front . . .	287	or	2·87	times	as strong.
On one side . .	116	„	1·16	„	„
On the other side .	116	„	1·16	„	„
Behind . . .	38	„	0·38	„	„

Of course, this disposition of the carbons is only of service when the light is required to be concentrated on one side of the lamp.

In some instances the light is maintained by an alternating current, and under such circumstances the 'crater and cone' formation of the carbons does not result, both carbons being more or less pointed, and consumed at equal rates. A lamp fed by such a current does not, therefore, direct so many of the light-rays downwards, as compared with a direct current lamp, but diffuses them more uniformly in all directions. For ordinary purposes the direct current lamps are to be preferred, for it rarely happens that the light is required to be directed upwards or even horizontally.

It is very difficult to ascertain the temperature of the electric arc, and it has been variously estimated. The positive carbon is probably heated to a temperature somewhere between 2,400° and 3,900° C., and the negative to between 2,100° and 2,500° C.

The phenomenon which we have referred to as molecular disintegration, and which is one of the distinctive features of the electric arc, may perhaps be more correctly described as a case of actual volatilisation. So far, it has been impossible, by any other means of heating available, to convert carbon into the liquid, much less into the gaseous condition. Were it possible to volatilise this highly refractory material, a knowledge of the temperature at which the conversion takes place would be useful in determining the actual temperature of the arc. It is, however, a matter of common knowledge that all bodies on being raised to the same degree of temperature become equally luminous, and that a given luminosity results from, or is dependent upon, a definite temperature. It follows from this, that if on different occasions, a carbon rod were raised to the same luminosity, it would be at the same temperature, and, *vice versâ*, if it were raised to the same temperature on different occasions, the light emitted in each case would be of the same intensity.

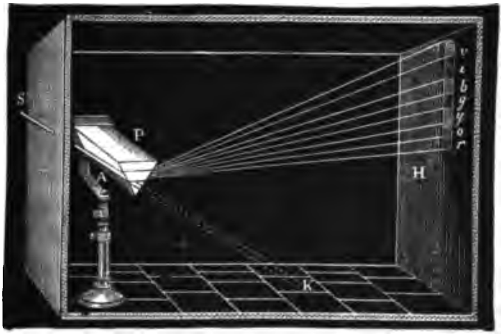
For the sake of those of our readers who are not acquainted with the character of a beam of light, a few words on the subject may not be out of place. Pure white light is in reality composed of rays of seven different colours superposed upon one another, or blended together. These colours are red, orange, yellow, green, blue, indigo, and violet, and it is by the simultaneous reception of these rays, in certain definite proportions, by the optic nerves, that the sensation of white light is conveyed to the brain. The generally accepted theory which endeavours to explain the manner in which a beam of light is propagated, is based on the assumption that all interstellar space, and likewise the space between the minute particles of all material bodies, is pervaded by that mysterious medium already referred to as ether.

A body may be said to be a luminous substance when it is a source of light-rays, such as the sun or a candle flame. Now the luminosity of a body is ascribed to an almost infinitely rapid vibration of its molecules; this vibratory motion is communicated to the ether particles pervading and enveloping the substance, and is propagated in all directions in the form of spherical wave-motions. The colour of the ray varies with or is determined by the rate of vibration. The velocity with which light travels is about 186,000 miles per second, and it has been calculated that the length of a wave of the extreme red end of the spectrum (that is to say, of a luminous ray having the lowest rate of vibration), is such that 39,000 such waves, placed end to end, would cover only one inch, while 64,631 of the extreme violet waves would be required to span the same distance. It follows that in one second, 464 millions of millions of red waves, and 678 millions of millions of violet waves, enter the eye and strike the optic nerves.

If a beam of solar light (S, fig. 253) is allowed to pass through a hole in the shutter or wall of an otherwise absolutely dark room, it will illuminate a small section of the floor, K, but if a prism or wedge-shaped piece of glass (P) is placed in the track of the beam of light, after the manner shown in the diagram, the beam will be diverted and the rays separated; on emerging and being allowed to fall upon the screen, H, or even on the wall of the room, it will be found to consist of the seven colours above enumerated. This many-coloured band of light is generally referred to as the spectrum.

If the beam is not of a pure white colour, the impurity or irregularity may be due to the chemical constitution of the source of light, or to varying degrees of luminosity. For example, if a beam from a red-hot substance is allowed to fall upon the prism, the decomposition or separation of the rays will not result in the formation of the seven coloured bands, those near the violet end of the spectrum being absent on account of the vibrations being nsufficiently rapid to produce them. When a source of ight is heated to different degrees of luminosity, the spectra resulting therefrom will consequently vary, while, on the other hand, if it is raised at different times to the same temperaure, and therefore to the same degree of luminosity, the spectra obtained will be identically the same in each case. Now it has been ascertained that the spectra of the white light emitted by he incandescent crater of the positive carbon are always identically the same, that in fact the same proportion between the various coloured bands is always evidenced, whence it is at once deduced that the temperature of that portion of the arc is always aised to the same point. This constitutes one great reason for ccepting the proposition that the transference of carbon particles rom the positive to the negative rod, is caused by a volatilisation t the former and a resolidification at the latter ; for, so far as xperiment has hitherto led us, there is for a given material, a onstant critical point of temperature at which a change from the olid to liquid or to the gaseous state ensues, and, the most important point of all, this temperature is not any further increased ntil the whole of the solid body has been so changed. It will be evident that the admixture with the carbon of any foreign body (all such bodies having a lower critical point of temperature han carbon), must lower the temperature at which volatilisation

FIG. 253.



ensues, and therefore reduce the luminosity of the crater. Moreover, when a body is transformed from the solid to the liquid or gaseous state, a certain amount of heat, known as the latent heat, is absorbed in the process. Thus one pound of ice at the freezing temperature absorbs about as much heat during its conversion into water at the same temperature, as would suffice to raise the same mass of water from the freezing temperature to 80° C.; whence the latent heat of water is said to be 80° C. On the other hand, when a liquid is solidified a corresponding amount of heat is given out during the change. Thus one pound of water at the freezing temperature in being converted into ice, gives out as much heat as would raise the temperature of the same mass to 80° C. Returning then to the electric arc, if the positive carbon is more or less volatilised, a certain quantity of heat is absorbed in bringing about the change, whence, on the carbon being resolidified on the negative rod, a corresponding quantity of heat is evolved.

These reactions have been made to account for a very remarkable phenomenon pertaining to the electric arc. It has been found that when the arc is established a back or counter E.M.F. is set up amounting to nearly 39 volts. This effect is somewhat analogous to that, accounting for the reaction which is set up when a current is sent through a voltameter, and which was fully entered into in the preceding chapter. The effect is also parallel to that remarkable feature in the action of electric motors, viz., the counter E.M.F. which is set up by the armature when it is caused to revolve in an established electro-magnetic field. In fact, the phenomenon affords a new demonstration of the law that every action brought about by any force, sets up a reaction or counter-force.

The theory of the existence of this counter E.M.F. does not, however, depend solely upon the assumed volatilisation and re-solidification of the carbon particles. It is a matter of general knowledge, and one which has given rise to many different conjectures, that the *apparent* resistance of the arc does not increase proportionally with the distance between the rods. The resistance of an arc of one-tenth of an inch appears, in fact, to be nothing like double that of an arc of one-twentieth of an inch. If, however, the resistance of the air space with its impregnation of carbon particles, were the only element entering into the question, the resistances in these two cases should be exactly as two to one. Now, experiments have been made with arcs of different lengths (the electro-motive force being also varied so as to keep the current strength constant), with the result that, allowing for a definite counter E.M.F. of 39 volts, there remained a resistance which, as we should expect, varied proportionally with the length of the arc, and affording thereby a demonstration of the actual existence of the counter E.M.F.

The great practical lesson to be derived from a knowledge of this effect is that the E.M.F. of the current which is passed through the lamp must always exceed 39 volts, or it will fail to maintain the arc, in just the same manner that an E.M.F. exceeding 1·47 volts must be employed to decompose water. It is in fact usual to provide an E.M.F. of between 44 and 50 volts for each lamp, the actual or net resistance of the arc itself, that is, of the air space separating the carbons when they are in the normal position for lighting, or at a distance of about 3 millimetres apart, being variously estimated at something between one-eighth and one-half of an ohm.

The resistance of prepared compressed carbon varies with the different makers, the resistance of one specimen amounting to 2,430 times that of a similar piece of pure copper, or nearly 4,000 microhms per cubic centimetre. The specific resistance of the comparatively impure and more crystalline gas-retort carbon has been shown to be about 17 times as great as that of the prepared material. The actual resistance of the prepared carbons ordinarily used for arc lamps is about 0·15 ohm per foot. In order to reduce this they are frequently coated with a very thin layer of copper deposited electrolytically. But great care must be taken that the metallic deposit is very thin, otherwise it will melt for some distance up the rod, and there will be a danger of fused globules falling off on to the glass globe and fracturing it. It may also be in sufficient quantity to decidedly tinge the flame of the arc with the characteristic green hue of burning copper.

The composition and method of preparing or manufacturing artificial carbons varies considerably, the precise details being in most cases regarded as trade secrets. Generally, however, finely pulverised coke forms the basis, this being intimately mixed with pure carbon powder derived from the destructive distillation of some such organic substances as gas-tar, pitch or bitumen. An adhesive substance, such as a syrup of cane sugar and gum, is then added to make a paste, the rods being shaped by forcing the mixture with considerable pressure through a die plate. The rods so formed are then baked in an oven a number of times, to decompose the carbonaceous compounds, and drive off the volatile constituents. Immersion in syrup usually takes place between the bakings. But great care is taken to remove any foreign substance from the ingredients, and so to ensure the production of a homogeneous rod, for, as will have been already gathered, the presence of foreign bodies in the arc causes fluctuations in its luminosity, and considerable variations in its colour.

The chief requirements which it is necessary that a carbon rod should fulfil are then, that it should be dense, that its molecular or mechanical structure should be uniform, that it should be pure, and that its electrical resistance should be low. The diameter of the rod varies with the light it is required to give or the current it is required to carry, those most frequently employed ranging from 7 to 10 millimetres in thickness, and these give an actual luminosity of about 875 candle-power per ⅔ horse-power absorbed, and approximately this may be taken as the power required and the actual amount of light emitted by an ordinary arc lamp. The usual practice of referring to the light of such a lamp as being of 2,000 or more *nominal* candle-power is, therefore, very misleading. The use of globes still further reduces the actual amount of light obtained from the lamp.

The proportion of light cut off by globes has been determined to be :—

For clear glass . . .	about 10 per cent.
„ light ground glass . .	„ 30 „
„ heavy „ „ . .	45 to 50 „
„ strong opal „ . .	50 to 60 „

Assuming an arc lamp to give a light of 875 candle-power when the current strength is 10 amperes and the E.M.F. 50 volts it will be evident that this amount of light is produced at a cost of 500 watts, so that were a lamp to consume one electrical horse-power or 746 watts, it should yield a light of about 1,300 candle-power. Allowing for the various losses in the conversions, it may be taken that on an average arc circuit, the engine indicates one horse-power for each ordinary or 875 candle-power lamp.

The Jablochkoff 'candle,' which was devised by M. Paul Jablochkoff in 1872, and which caused considerable excitement at the Paris Exhibition of 1878, is undoubtedly the simplest form of arc lamp yet introduced, although, as it is not economical, it is used less extensively than it otherwise would be. The candle consists of two pencils of prepared carbon about 22 centimetres long and 4 millimetres in diameter, fixed parallel to one another but separated by a strip 2 millimetres thick, of some fusible non-conducting material such as kaolin. Pieces of split brass tubing, 5 centimetres long, are placed over the lower ends of the carbon pencils and serve to form connection with the holder which is attached to the base of the lamp. The upper ends of the pencils are scarfed, and a small lighting fuse consisting of a paste of plumbago and gum serves to connect them together electrically and affords a path for the initial flow of the current. This fuse is speedily consumed and the arc established. The consumption of the positive, as compared with the negative carbon being with a direct current approximately as 2 : 1, an alternating current is employed, so that the pencils are uniformly consumed, the insulating material also being burnt at the same rate. Each candle lasts about an hour and a half, and owing to the interposition of the insulating strip, that is, to the separation of the carbons, a candle after having been once extinguished cannot be re-ignited unless a fresh lighting fuse is added, or the pencils temporarily connected by a piece of wire, or another piece of carbon.

The lamps are joined in series on a circuit through which a current of eight amperes is sent, the potential difference necessary at the terminals of each lamp being about 42 volts. The rate of consumption of electrical energy is therefore about 336 watts, and this is sufficient to yield, from an open light, a luminosity of 400 actual candle-power.

It is customary to fix a number of candles, generally four, in a lamp, and consume them in succession. In this way, the light can be maintained for six hours without any attention being given beyond that of turning a switch, so as to divert the current from one candle to another. The form of candle-holder most frequently employed consists of two short rigidly fixed pillars, one of them being slotted so as to allow a small play for a triangular piece carrying the socket for one of the carbons, the other socket being cut in the other pillar. A stiff flat spring presses against the free corner of the triangular piece, which can be moved to and fro in the pillar. On pressing the candle in between these pillars, a good mechanical support, as well as good electrical contact, is afforded.

There are two kinds of lamp bracket for supporting the holders. In one of them, one pillar of each of the holders is electrically connected to a common terminal, the other pillars being connected each to a separate terminal, so that at least five leads are necessary. In the other type each candle has a separate holder, each holder requiring two terminals and a distinct pair of leads from the switch.

Sometimes a switch is placed on or near each lamp, but it is more general to divide the lamps into a number of separate circuits, each circuit comprising four lamps joined together in series and manipulated by a single switch placed in the dynamo-room.

An automatic arrangement is also employed to avoid the risk of burning the candles right down to the sockets and so causing a disconnection. The apparatus consists of a vertical solenoid with a core which is provided with two pairs of contacts. Should the circuit be broken by one of the candles 'going out,' the core falls and two of the contact points fall into mercury cups and complete the circuit of an electric bell. At the same time the other pair of contacts drop into mercury cups which complete the circuit through the second series of lamps. The attendant has then only to shift the leading wire to the terminal block of the next circuit in readiness for his next act of negligence.

The Jablochkoff system has very few advocates in England, chiefly on account of its cost, but it is a very simple system and one which finds great favour in such places as the Indian palaces, where money is not scarce, and where skilled labour is practically unprocurable. Other forms of electric candle have been devised, but as they are all now extinct, we need not pause to consider them.

Another class of arc lamp, frequently called the semi-incandescent, used, however, with a direct current, is typified by the Werdemann lamp, which consists of a large rounded block of carbon connected to the negative lead and supported by a hinged bracket. The positive lead is connected to a thin pointed carbon rod, and, by means of a weight attached to a cord working over a pulley and fastened to its lowered end, this thin rod is kept in contact with the hinged block. Both carbons become incandescent at, or in the vicinity of the point of contact, and a small circular arc is struck. The rod is of course somewhat rapidly consumed, and a hole gradually formed in the carbon block. Great things were expected of this lamp, but it did not prove economical; it was very variable, flickered considerably, and is now practically obsolete.

Our chief object in referring to these lamps, was to give some little idea of the channels into which men's minds were directed in their earlier efforts to 'subdivide' the electric light, or more correctly speaking, to maintain a number of comparatively small lamps on one circuit.

Coming now to the question of arc lamps in their present state, it would be convenient if we were able to classify them, or divide them into a few distinctive types, but there is absolutely no simple or natural classification, and a complicated or forced division would be undesirable.

Many efforts have been made to obtain a precise but comprehensive classification, with the result that there are virtually as many classes as there are lamps. It would be possible to divide the lamps into two classes, viz., those used in series, or on a circuit through which a *constant current* is sent, and those used in parallel, or which have a *constant potential difference* maintained at their terminals. The latter kind are comparatively simple, but any lamp of that class could be transferred to the other by an alteration in the winding of the coils and by the addition of a 'cut-out' device, to automatically short-circuit the lamp, in the event of a disconnection in the arc-circuit.

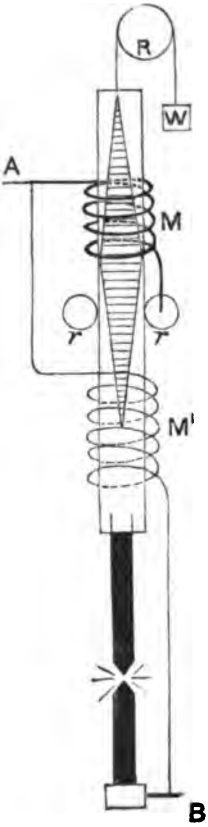
This system of classification, therefore, can scarcely be said to be satisfactory. It is, however, an important feature that the series system is characteristic of the arc lamp, owing to the fact that the main leads need only be small as compared with those necessary for parallel working. With the small current usual on a series circuit, the loss due to the resistance of the leads is trifling as compared with the loss that would be experienced were the same leads used for parallel lamps. For this reason parallel arc lamps are not often used, although they have the advantage that they can be so adjusted as to render it possible to join them in parallel with incandescent lamps. In all cases it is essential that the lamp should automatically 'strike' its own arc, or cause the carbons, when in contact, to separate to the required distance; and this action must perforce be controlled by the main current, that is to say, the separation of the carbons must always be brought about electrically, and the coil used for the purpose must always be placed in the main circuit. This coil is usually referred to either as the main, or the series coil, the latter term being employed because the coil is joined in series with the carbons. When lamps are joined up in parallel, a small resistance coil is placed in series with each lamp for steadying purposes. Without this resistance, a slight variation in the length and resistance of the arc, or the reduction in the resistance of the carbons as they burn away, would cause a sensible variation in the current strength; but the use of a resistance coil reduces the percentage of the variation in the resistance of the particular branch, and therefore keeps the current strength more nearly uniform. To compensate for the loss of power in the 'steadying' resistance, the E.M.F. provided is about 5 volts higher than that provided per lamp when joined in series. With lamps joined in series this extra resistance is unnecessary, because when the resistance of any one lamp varies, the current strength is not appreciably affected; the other lamps in circuit with it, in effect, act as a steadying resistance, and tend to keep the current strength constant.

If the source of light is for focussing purposes required to remain stationary, which is, for lighthouse or lantern work, of paramount importance, both carbons must be automatically movable, at their respective rates of consumption; but when this is not absolutely necessary, as, for example, in ordinary street or shop lighting, then it is only necessary that one carbon should be fed forward towards the other, which is supported in a fixed socket, and which gradually burns away. The latter form of lamp is, as a rule, simpler in construction and correspondingly cheaper than the former, or 'focussing,' type, but in this case, too, classification is out of the question, as the one form can be easily converted into the other.

It might also be possible to divide lamps into alternating and continuous current lamps, but this classification would be unsatisfactory, for little if any fundamental difference in the principles of construction are involved. One point may, however, here be mentioned, and that is, that with lamps used on alternating-current circuits, it is necessary that the cores of the electro-magnets should be short and laminated in order to minimise self-induction and eddy currents, and so enable them to respond quickly to the reversals.

We should like to divide lamps into two classes, viz., those in which the 'feeding' forward of one or both of the carbons is controlled mechanically, and those in which the controlling agent is electricity alone. But we are here met with another difficulty, for even those in which mechanism is employed for feeding, require the intervention of the current to release or start that mechanism. The simplest 'mechanical' lamp would be one in which the upper carbon feeds downwards by gravitation, that is, in virtue of its own weight, when the current passing through the coil used for striking and maintaining the arc is incompetent to overcome this force of gravitation; and we shall see, in the Gulcher lamp, that this degree of simplicity is in great measure approximated to. The Gulcher is, however, a parallel lamp, and the principle is only applicable to such. When the lamp is used on a series circuit it is necessary to provide a second coil, which, by acting in opposition to the striking or series coil, feeds the carbons forward when the length of the arc becomes too great. This second solenoid is joined across the lamp terminals, forming a shunt to the series coil and the arc. The striking or series coil placed in the main circuit is of low resistance, while the feeding or shunt coil is of high resistance, the proportion of the resistances being usually about 1 : 100. As these coils have antagonistic effects, the lamps may be called 'differential.' It will, however, be observed that some of these so-called electrically controlled lamps involve delicate mechanical contrivances. To be purely electrical, the moving carbons would require to be perfectly balanced and only movable under the preponderance of the effect of one coil over that of the other. But no such lamp is now in practical use, so that for this and other specified reasons the division into mechanical and electrical control falls to the ground. The nearest approach to an electrically controlled series lamp is the Pilsen, the only deviation from the principle being the addition of a small weight to the upper carbon holder.

FIG. 254.



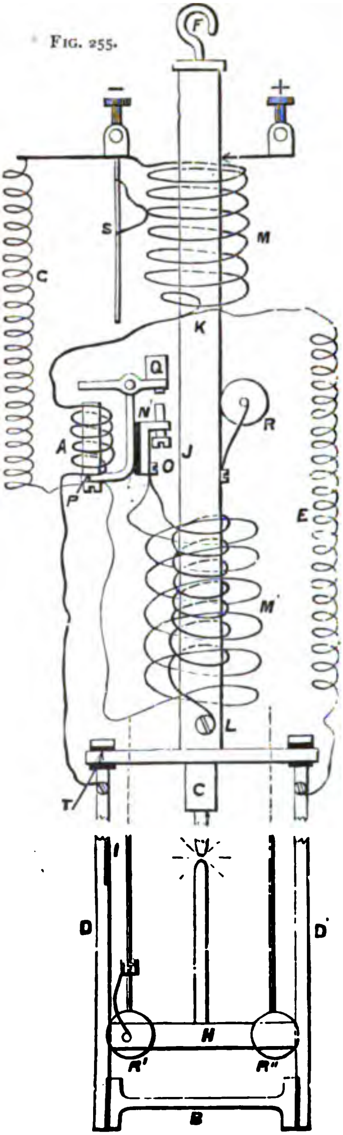
The fundamental principle upon which the differential arc lamp is constructed, is clearly indicated in fig. 254. The current on arriving at A is divided between the two paths, one of low resistance, and the other of comparatively high resistance. The former, or main circuit, includes the thick wire coil M, from which the current passes to the contact guide roller *r*, and from thence through the frame to the upper or positive carbon holder, the circuit to B being completed through the arc and lower carbon holder. The other, or shunt, circuit consists of the coil M^1, which comprises many turns of fine wire, its ends being connected to A and B respectively. These coils are, in the lamp to which the diagram more particularly refers, wound upon a brass tube, inside which another brass tube is loosely fitted, so that it can slide up and down freely. The shape of the soft iron core is in this case like that of two long cones placed base to base; this core is fixed inside the inner tube, and is balanced by a weight W attached to a cord passing over the pulley wheel R.

The resistances of the coils M and M^1 are so adjusted that, the arc having been struck and having arrived at the proper length, the action of the coils upon the core is exactly balanced. Any increase in the resistance of the main or series circuit, caused by an increase of the length of the arc, disturbs this balance, increasing the current through the shunt coil, whence the core, with the upper carbon attached, is attracted downwards by the shunt coil, and in descending again restores the balance, readjusting the arc to its previous dimensions. It will thus be seen that in the event of a disconnection in the arc circuit such as might happen before lighting up, the coil M^1 takes the whole of the current, and continues to draw the core down until the two carbons enter into contact. Immediately this happens a heavy current passes through M at the expense of M^1, and the core and upper rod are raised just sufficiently to establish the arc. It may here be observed that were the core made of a simple cylindrical rod of iron, it would have a tendency to balance itself, or take up its position in the middle of the electro-magnetic field produced by the two coils ; and although a variation in the magnetisation of either solenoid would move the core away from that position, it would manifest a tendency to return to it, and in so doing cause fluctuations in the arc. By using the conical core this difficulty is overcome, because as the magnetisation of the preponderating solenoid increases, and attracts the iron, it acts upon a gradually increasing core, so situated that it can never get into its 'best position,' but remains steady at any point in a comparatively long range.

Fig. 254, while serving to illustrate the general principle involved in differential lamps, is really a skeleton diagram of the Pilsen, (which was invented by Messrs. Piette and Krizik of Pilsen, a town in Bohemia,) and which, while simple in construction, works with remarkable steadiness, even under somewhat considerable fluctuations in the current. It has also the advantage that it is practically noiseless.

It has recently passed into the hands of the Gwynne-Pilsen Co., who have simplified some of its details and effected other structural improvements without, however, interfering with its fundamental principle.

FIG. 255.



A detailed diagram of the lamp is given in fig. 255. The coil-frame J and casing are electrically connected to the positive terminal +. From J the current is transmitted by contact rollers R to the inner brass tube C (containing the double conical iron core), and thus through the holder to the positive carbon. Thence it passes through the arc to the negative carbon holder H, and from thence through the contact rollers R′ R″ to the negative guide rods D, D^1, both of which are insulated from the bottom plate of the lamp, as well as from each other at B. The current being thus divided, one part (the lesser) passes through the iron wire coil E, and the greater part through the automatic cut-out coil A, these two branches reuniting at K, and thence passing through the main coil M to the negative terminal marked −, from which it is carried to the positive terminal of the next lamp in series, or the negative terminal of the dynamo, as the case maybe. The negative holder is supported by two cords which pass over pulley wheels and are connected to the brass tube containing the core. This is more clearly indicated in fig. 256, where the cords are shown connected to the rods attached to H, R R′ being the pulley wheels.

One of these wheels, R′, has very fine teeth cut round it, into which the click, which is to be seen above the wheel, engages, so as to allow the wheel to rotate freely for feeding, but to prevent it moving in the reverse direction. The cord, therefore, during the separation of the carbons has to *slide* along the groove, sufficient friction being in that way introduced to prevent sudden or jerky separations.

Were the two holders exactly equal in weight they would counterbalance, but in the more recently constructed lamps, the positive holder is about 1½ ounce heavier than the negative, so that when no current is flowing the carbons run together.

The action of the series current then is to draw the iron core, to which the positive carbon is attached, up into the coil M, thus striking and maintaining the arc. In order to regulate the lamp, a shunt-current is taken from the screw L, and passed round a solenoid of stout copper wire, to the insulated bracket O, and returning from thence through the shunt-coil proper M^1, consisting of many turns of fine copper wire (wound in the same direction as the spiral of L), having its other end attached to the bracket P of the automatic cut-out, from whence it passes through a coil of stout German-silver wire G to the terminal marked —. The number of convolutions of the coil M^1 and their resistance are so proportioned that (when the arc has been drawn to a length of about ⅛ inch) the attractive action counterbalances that of the main coil M and the small extra weight of the positive holder. Equilibrium being thus established, the arc is maintained at its normal length and resistance, so long as the current is kept constant. If from any accidental cause (such as the fracture of a carbon, mechanical injury, or the breakage of a cord), the main current cannot flow from C to D and D^1; then the magnet A of the automatic cut-out fails to hold down its armature, which by reason of the weight on its unattracted end falls in the opposite direction, and establishes a contact with the screw N on the insulated bracket O, thus opening a path for the main current *viâ* L, O, N, Q, and G to the lamp terminal marked —, and so preventing a complete break of circuit or the destruction of the shunt-coil M^1.

The negative guide rod D^1, is fitted with a strip of ivory insulation I, so situated, that when the carbons are nearly burnt out, the contact roller R^1 ceases to make contact, the current ceases to flow round the magnet A, Q falls, and the lamp is cut out of circuit. The function of the alternative path from R$''$ through D^1 and of its iron resistance E is that when the lamp is burning, the resistance E causes the greater part of the current to pass *viâ* D, thus securing the efficient action of the magnet A, and preventing the lamp from becoming prematurely cut out. When owing to exhausted carbons the lamp is in process of cutting out naturally, the contact roller R^1 in passing from D on to the insulating strip I, would carry an arc after it from R^1 to D, were it not for the temporary path afforded from D^1 through E, until such time as the main current had been diverted through the path L, O, N, Q, G. The German-silver coil, G, has no action upon the working of the lamp; it is a compact form of resistance, equivalent to the apparent resistance of the lamp, to be thrown into the main circuit, when the lamp is cut out automatically; it is superfluous with a self-regulating dynamo.

A view of the interior of the lamp is given in fig. 256, in which the lettering corresponds to that employed in the diagram, fig. 255. It will be observed that a means of final adjustment is provided by the movable contact S, which can be used to cut out one or more of the convolutions of the main coil M. The friction roller is here lettered *r*, and as already mentioned, R R$'$ represent the pulley-wheels over which the cords connecting the positive and negative holders together, are passed.

A sectional view of another form of the lamp is given in fig. 257, in which the two coils M and M^1 are wound on the same bobbin, but in opposite directions. The long conical core is clearly shown at D. The negative holder is suspended in the same way as in the bi-conical form, but the pulleys and other parts such as the cut-out are not shown in this figure. The lamp is also made with horizontal carbons, so as to render it suitable for rooms with low-pitched roofs, and it will be seen that the absence of mechanical control facilitates considerably the alteration in the design. It should be added that the workmanship of the Pilsen lamp is of the highest order; the finish is unusually good, and all pulleys, rods, and the working parts generally, are electroplated.

Another very simple and efficient lamp is that invented by Mr.

FIG. 256.

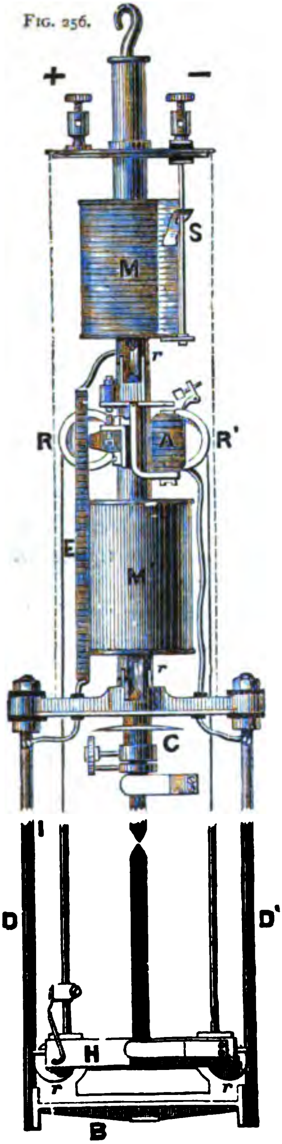
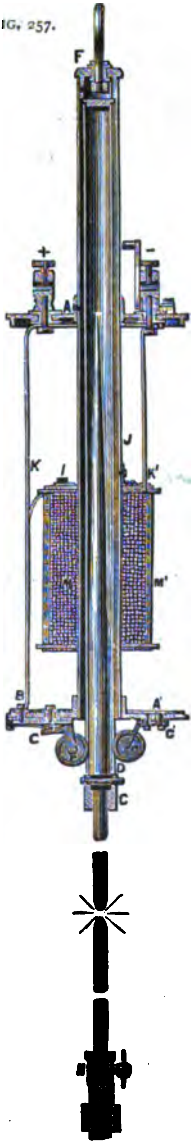
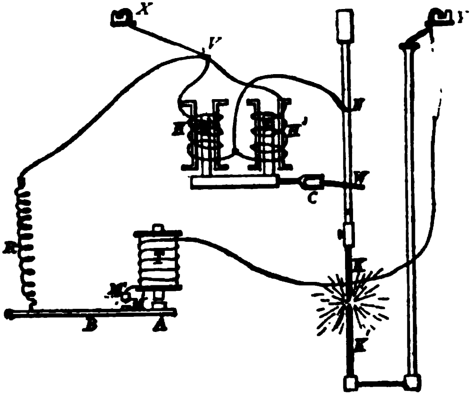


FIG. 257.



C. F. Brush. It was one of the first and it certainly remains one of the best of modern arc lamps. A great feature in its favour is the extreme simplicity of the mechanical contrivance. The principle is illustrated in fig. 258. The terminals X Y usually take the form of a pair of brass hooks which, by being dropped over horizontal pins on the under side of a suspending board place the lamp at once in the main circuit. The negative carbon K′ is fixed, and, being gradually consumed, the arc is steadily lowered in position, the upper or positive carbon K, falling at a corresponding rate.

FIG. 258.



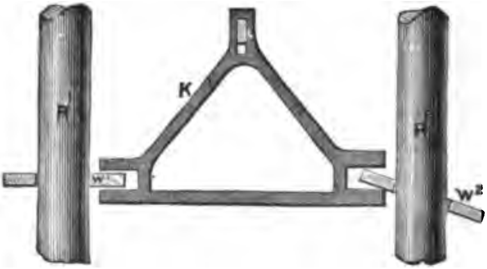
The current enters the lamp at the positive terminal X, and divides at V in the main circuit, passing through the low resistance coils H H′, in parallel in such a way as to generate powerful but opposite poles at the lower ends of the solenoids. On leaving the coils the currents reunite, and passing by a wire to the upper carbon holder N, traverse both carbons, the lower of which is connected to the negative terminal Y. The shunt circuit, the resistance of which is 450 ohms, is made by a thin wire passing from X round the bobbins H H′ in series, then round the cut-out bobbin T, from which it passes direct to the terminal Y. The thin coil on H H′ is wound outside the main coil. Connection is also made between V and the pivoted lever B, by means of a wire and resistance spiral R, but this will be again referred to presently.

Assuming the carbons K K′ to be in contact, the passage of the main current through the coils H H′ causes the soft iron cores N S and their horizontal yoke-piece to be drawn upwards. The yoke-piece is provided with a fork C, which tilts the washer-clutch W, causing it to seize the carbon holder and raise it sufficiently to strike the arc. Under normal conditions only about 1 per cent. of the total current passes through the shunt coils, but when the arc increases in length and thereby raises the resistance of the main circuit a proportionally larger current passes through the long thin wire coils on H H′. Being wound in the opposite direction to the few turns of the main coils, the shunt coils cause a diminution of the magnetisation of the cores or plungers N S, which therefore fall, and, causing the clutch W to loosen its grip of the holder, allow the positive carbon to fall, by the force of gravitation, until the length of the arc is so far reduced as to re-establish the normal division of the current through the main and shunt coils. We see then that the function of the thick wire coil is to tilt the clutch and strike the arc, while that of the shunt coil is to level the clutch, allowing the rod to slide and feed the carbon downwards. As a rule these reactions take place so gradually that the upper carbon is maintained at a uniform distance from the lower, and is simply fed at a rate corresponding with the consumption.

The 'cut-out' coil T performs a most important function. It is evident that should one of the carbons be burnt away or broken, or should from any other cause the maintenance of the arc become impossible, some device is necessary to introduce into the circuit an alternative path of about the same resistance as the arc circuit. The way in which this is accomplished in the Brush lamp is ingenious. It will be remembered that the shunt circuit includes a coil of many turns of thin wire on the bobbin, T. Now when the main circuit is broken, the whole current has to pass through the shunt circuit, and the coil T is so adjusted that when this increased current passes through it, but not otherwise, its core becomes sufficiently magnetised to raise the armature A, and with it the lever B. This lever carries the small contact stud M, and this on rising makes contact with another stud M′, which is connected to a short thick wire coil round T, the other end of which is connected to Y. It follows that under such circumstances a low resistance circuit is established from V, along R, and B, to M, and so on to Y.

Were it not for the high resistance of the shunt coils, they could be employed for this purpose, but under the circumstances such a plan is obviously impracticable. Of course as the main circuit is disconnected, the positive carbon-holder is not interfered with by the clutch, and can therefore, if only a portion of the carbon has been broken off, descend and re-establish the arc, when the current flowing through the thick coil on T will be diminished and the cut-out circuit disconnected.

FIG. 259.



Usually the Brush carbons are a foot long and last for eight hours or thereabouts. When, however, a longer period of lighting is likely to be required, lamps with two pairs of carbons are employed. The device for 'changing-over' from one pair to the other is purely mechanical and is illustrated in fig. 259. The positive carbon-holders R^1 and R^2 are parallel one to the other, and each is furnished with a washer clutch, as shown at W^1 and W^2. These clutches are operated by a small frame K, which is supported by the lever (shown in section at L) attached to the plunger or soft iron core of the striking and feeding solenoids. By the very simple device of making one of the forks in the frame K, higher than the other, this higher fork tilts its clutch before the other begins to act, and consequently lifts its corresponding carbon-holder a greater distance than does the other. At the moment when the first carbon is raised, it is short-circuited by the other, which the next moment is also raised. The arc then establishes itself across the lesser distance, and in all subsequent feeding and controlling movements the pair of carbons across which the arc was first started are alone affected, because, although both positive carbons are raised and lowered together, the ends of the reserve carbons never come into contact, and the E.M.F is insufficient to start an arc across the air space which separates them. When the one pair of carbons have been so far consumed that they cannot meet when the frame falls, the circuit is completed through the reserve carbons, and the arc established, after which it is maintained by the same apparatus acting in the same way as with the first pair.

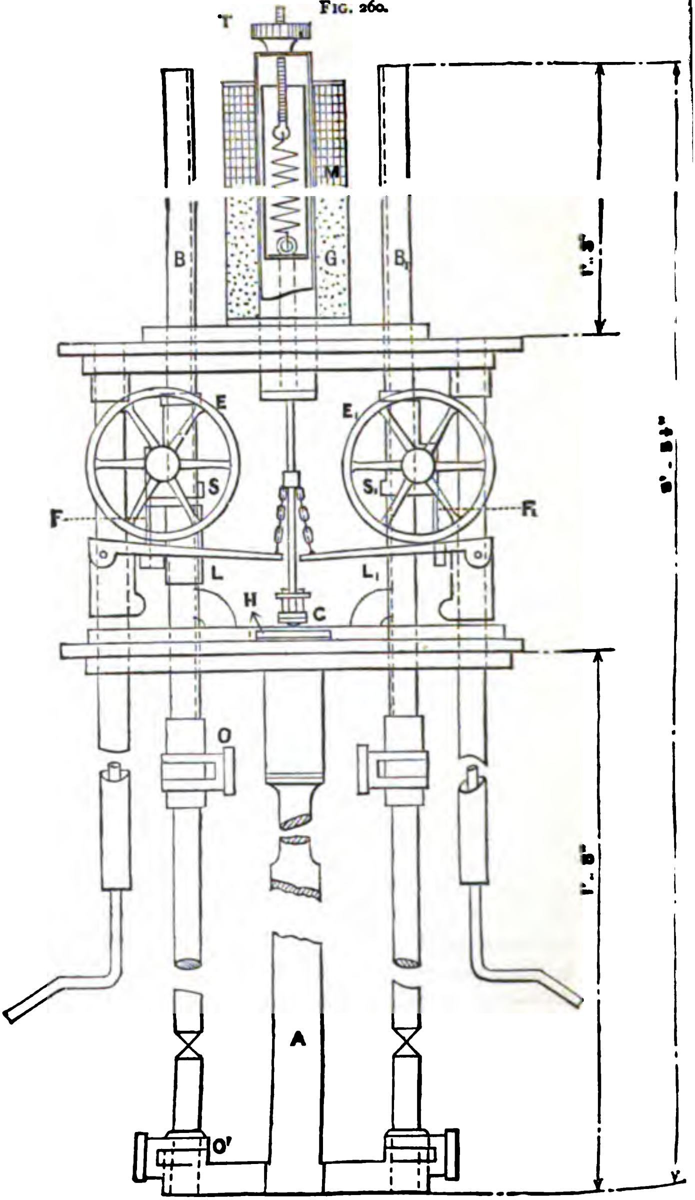
The construction of the double arc lamp invented by Messrs. Crompton and Crabb is illustrated in fig. 260.

The two positive carbons are carried by the rack-rods B and B_1. Sliding on each of these is a light gun-metal sleeve, S S_1, carrying spindles, to which are attached the two large brake wheels, E E_1, and between them the pinion which gears into the racks. These brake wheels rest upon a pair of levers, L L_1, the outer ends of which are pivoted to the framework of the lamp, their inner ends being connected by links to the core of the solenoid, which is placed in a central position vertically above the two inner ends of the levers. This solenoid is differential, G being the shunt and M the main coil, and the core is partially supported by a spring. The tension of this spring can be regulated by means of the screw T, which is turned to the right to increase its length, and to the left to decrease it.

Projecting vertically downwards from each sleeve, S S_1, to a distance from the centre of the spindle about equal to the radius of the brake wheels, is a stout pin or finger, F F_1, the action of which is interesting.

Suppose the rack-rod to be drawn up, then if the lever be pulled by the solenoid above the horizontal position, the whole weight of the rod and carbon is supported on the edges of the brake wheels, and the friction of them on the surface of the levers is sufficient to prevent their revolution ; hence this rack-rod cannot run down. But if the levers be below the horizontal, then the weight is carried by the finger projecting from the sleeve, as shown at F ; the wheels are free to turn, the rack runs down, and continues to do so until the positive and negative carbon points come in contact. Now, if the current be switched on by its passage through the main wire of the solenoid, the levers rise, striking the arc, and at the same time applying the brake to the wheels. The combined action of the shunt and main currents on the solenoid core automatically adjust the length of the arc. If this becomes too great the increased current through the shunt draws down the core and levers, the brake wheels are left free to revolve, and the arc shortens. On the other hand, if the carbon points be too close

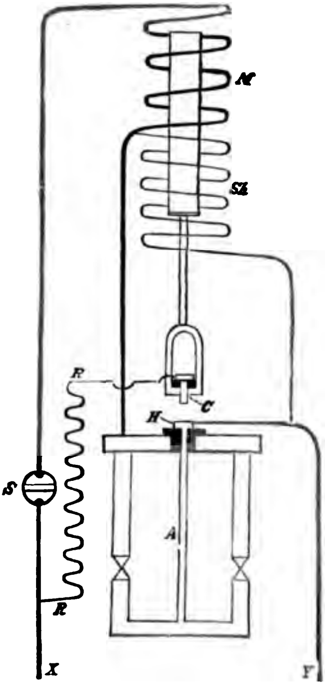
FIG. 260.



the levers are raised, bringing with them the rack-rod and upper carbons. The fact of the finger projecting from one sleeve being longer than that from the other determines which pair of carbons shall begin to burn first, because, on switching on, that pair which has the longer pin will be the last to break contact, and will therefore originate an arc in so doing.

It will be seen from the diagram that on the core being raised the lever L_1 will apply the brake before the lever L does. Hence, it may be said, that the rack-rod B_1 gets a start on B; its carbon points are separated before those of B, and are kept a greater distance apart until the latter are consumed. At this stage the rack-rod B is prevented from further fall by a stop, and can no longer feed; hence the arc will lengthen, the shunt current will increase, and the other rod B_1, which can still feed, will be allowed to descend until its carbons touch, starting a fresh arc. When the second pair of carbons have burned low, the same action takes place, viz., further descent of the rod is prevented, the arc lengthens, the shunt current increases, and the core is drawn down, but lower than when the first pair of carbons were burned out, until a copper stud, C, attached to it makes contact with another stud, H, connected to the negative pole, thus cutting the lamp out of the circuit, and introducing an equivalent resistance.

FIG. 261.



The connections of the lamp and its equivalent resistance coil are shown in fig. 261. The current entering at X finds two paths open; the one through the resistance coil R R and insulated contact piece C, which for the time being is resting upon H, and thus

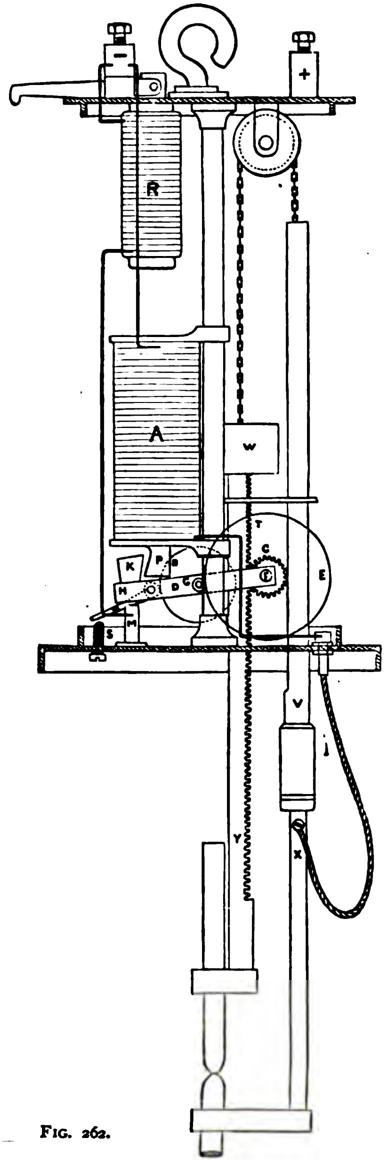


FIG. 262.

on to the next lamp; and the other through the switch S (which we suppose to be closed), the main solenoid coils M, the framework of the lamp, the positive carbon, the negative carbon, and ultimately out by H, and Y, on to the next lamp. The latter portion of the current in passing round the core magnetises it and draws it up, thereby breaking contact between C and H. Since nearly the whole of the current must now pass through the main solenoid, the core of the latter is definitely drawn up, lifting the two rack-rods, and establishing the arc between one pair of carbons, as explained above.

The Phoenix arc lamp is also of the differentially wound class. Its construction is illustrated in fig. 262, where A represents an electro-magnet wound with two coils, the pole-piece, P, of which acts upon an armature, K, fastened upon a frame H D, pivoted at F. This frame also carries a brake wheel B, on the axle of which is fastened a small pinion G, and brake lever N made to grip B by a helical spring wound round the axis, by which it is attached to the frame H D. The pinion G gears into the larger toothed wheel E, on the axis of which is a pinion C engaging with the rack R of the positive carbon rod. This rod carries a weight W, which enables it in descending to lift the negative rod V X. When no current is flowing the brake lever N rests on the screw S, which releases the brake wheel and allows the carbons to come into contact. The current enters at the positive terminal on the right hand of the figure, passes through the framework of the lamp to the rod Y, and thence to the positive carbon. It returns from the negative carbon by the insulated rod X and flexible wire attached to it, passing through the thick wire coil on A, and from this to the negative terminal. The magnet attracts K, raising the frame H D, thus causing the lever N to grip the brake wheel and, by turning E and C, to raise Y and lower X for the purpose of separating the carbons and forming the arc. As the carbons consume, the difference of potentials at the terminals rises and the current in the fine wire coil round A, which is connected as a shunt to the lamp terminals, increases. This weakens the electro-magnet A and allows the frame H D to fall and the carbons to approach. When the lever N comes in contact with the screw S, the brake is released, allowing the carbons to approach as the consumption continues. If the carbons burn out, or if from any other cause the circuit through them is broken, the frame H D drops on the contact pillar M ; this completes the circuit from the lamp frame through the German-silver resistance R to the negative terminal, thus preventing a break in the continuity of the circuit when several lamps are joined in series.

The Brockie-Pell arc lamp is illustrated in fig. 263 ; the main and shunt coils are wound on separate bobbins fixed parallel to one another, the main or series coil being that on the left side of the figure. The two cores pass through the ends of, and operate a 'see-saw' lever which is pivoted at its centre. The two carbon-holders are connected by a cord passing over a pulley wheel pivoted on the base of the lamp-case. The upper or positive holder is provided with a rack-rod which gears into a pinion ; the spindle of this pinion works in the frame of the lamp and carries a comparatively large wheel having a strong broad rim, against which a brake in the form of a small leather roller is applied. The lever carrying this brake turns on the weighted sector-shaped lever, which is loosely pivoted but moves solidly with the brake wheel, its descent being, however, limited by a stop; the

FIG. 263.

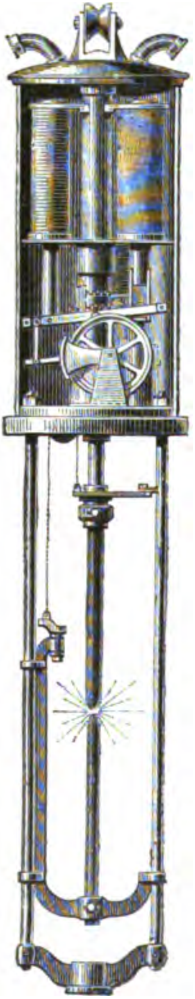
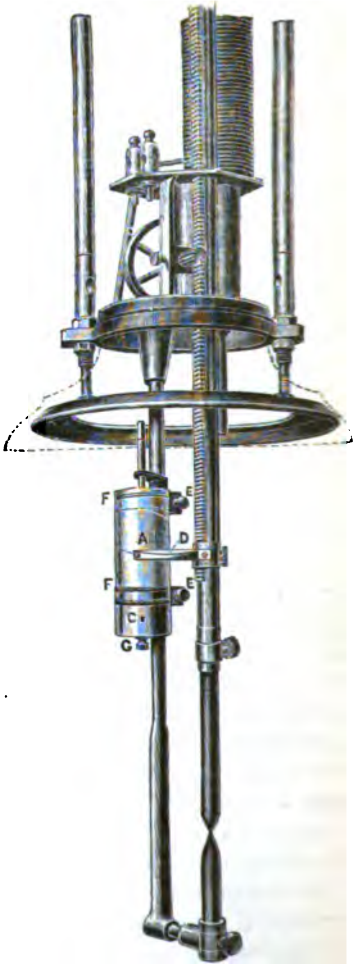


FIG. 264.

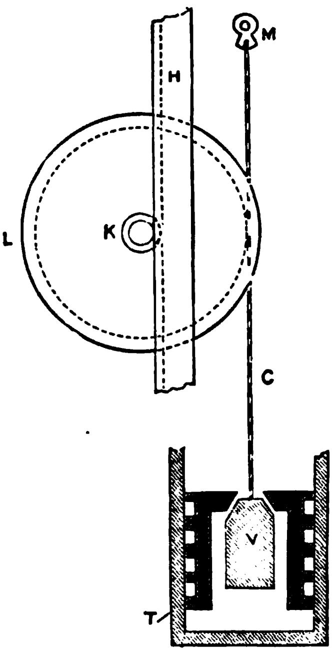


outer end of the brake-lever is connected with the link supported by the see-saw lever. The action of this mechanism can be readily understood. On the passage of the current the left-hand coil raises its end of the lever, applies the brake to the wheel, and raises the positive carbon, the negative carbon being caused to recede at the same time. The arc is therefore established. As the arc lengthens and the main current diminishes, the shunt current increases and the other end of the see-saw lever is elevated: consequently the brake lever is depressed, the brake wheel released, and the carbons allowed to feed together. These reactions take place readily, the feed being practically continuous, and a very steady light is the result. The initial adjustment for balancing the carbon-holders to operate with any particular strength, is effected by means of weights. As compared with the majority of lamps, the mechanism is simple and strong.

In fig. 264 is illustrated a form of arc lamp devised by Mr. J. G. Statter for workshop use. The lettered portion of the apparatus does not form a part of the lamp, but is attached for experimental purposes and will be explained presently.

The lower carbon is fixed, and the upper one is carried by a rack-rod which engages with a pinion carried on a horizontal spindle. On this same spindle, and just behind the pinion in the figure, is fixed a large grooved wheel round which passes a small chain. One end of the chain carries a peculiarly shaped weight, and the other end is fixed to the lower extremity of the core of the regulating solenoid, seen to the right at the top of the figure. Fig. 265 illustrates this arrangement more clearly, and also gives a section of the weight. H is the rack-rod which carries the upper carbon, and engages with the pinion K, while L is the large grooved wheel, on the same spindle as K, round which the chain C passes once. M is the point at which the chain is fixed to the core of the regulating solenoid. When it is required to separate the carbons and strike the arc, the core is sucked upwards into the solenoid, and pulling the chain upwards, causes the wheel L to revolve. This motion is imparted to the rack-rod by the pinion, on the well-known wheel and axle principle, and the upper carbon being lifted through a small distance, the arc is struck. The chain is prevented slipping round the wheel, by the weight at its lower end. This weight is designed to prevent any sudden jerky movement of the rack-rod : it slides inside a brass tube T, and is made in two parts. The larger part is cylindrical in shape, having a series of grooves on the outside (as in some forms of high-speed pistons), and fitting accurately inside the containing tube. The inner portion, V, to which the chain is attached, is a valve whose seating is formed in the top of the outer weight. As all the surfaces fit closely, the compound weight cannot be drawn upwards quickly, but it may be lowered freely, since the valve then opens and allows the imprisoned air to escape. So long as the arc remains of the proper length, the pull of the regulating solenoid on its core keeps the chain taut, and by preventing the rotation of the wheel, holds the carbon in position. But when the distance between the carbons increases and it is required to feed, the current through the solenoid decreases and allows the core and the upper part of the chain M to drop slightly: the weight then touches the bottom of the tube, and the grip of the chain on the wheel being loosened, the wheel is free to move, and the carbon and rack-rod move downwards by their own weight. Immediately the proper length of arc is restored, the core again pulls at M, lifting the weight and fixing the wheel and rack-rod in position once more.

FIG. 265.



But it is necessary to arrange that the feeding shall be as delicate as possible, that is to say, the carbon must move downwards very slightly immediately the arc becomes even the least trifle too long. It will be observed that when the weight descends the outer portion reaches and rests upon the bottom of the brass tube first. The valve weight V is considerably the lighter part, and has a small amount of free play after the heavier part is resting on the bottom. Now the weight of V is just sufficient to allow the chain to grip the wheel and hold it in position, and when the lamp is running under normal conditions, this is the only portion of the weight acting; extremely light touches of V on the bottom of the tube slacken the chain enough to allow the wheel to move slightly, and a delicate feed is thus attained.

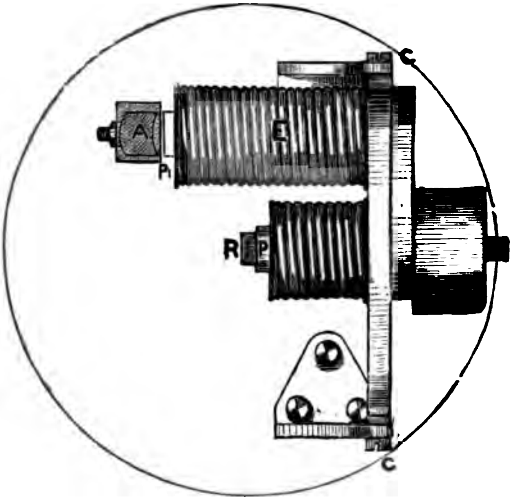
The lamp described is designed for constant potential or parallel working, but when it is required for use on the constant current or series system, the usual differential winding is employed, the resistance of the shunt coil being 100 ohms.

In another type of this lamp, the same feeding method is employed, but a different mode of striking the arc is adopted. The bearings of the brake-wheel spindle are carried by a lever, one end of which is connected to the core of the regulating solenoid; the rack-rod is then raised by the lever, without turning the wheel, to strike the arc.

Referring now to the experimental apparatus attached to the lamp in fig. 264. This illustrates an arrangement devised by Mr. Statter for the purpose of recording automatically the rate and regularity of the feeding of the carbons. A is a drum revolving about a vertical axis, and driven by a clock in the case C, just below A. One complete revolution is made per hour. The drum is covered with a sheet of ordinary squared paper. A light rigid arm, D, is clamped to the rack-rod, and carries a pencil which is kept pressed against the paper by a light spring. The distances on the squared paper parallel to the axis of rotation represent in fractions of an inch the length of carbon burnt; while one-sixtieth of the distance round the circumference corresponds of course to one minute of time. Before switching on the current the drum is given a complete revolution by turning the nut G, and the length of the arc struck is then recorded; this appears as a short vertical straight line on the paper. The drum then commences to rotate, while the pencil travels steadily downward with the upper carbon-holder. The method is practical, and is very useful for the testing of lamps and carbons.

The Gülcher lamp was designed for constant potential or parallel working, and has, therefore, neither a shunt coil nor a cut-out. It is consequently very simple in construction, as will be gathered from the plan given in fig. 266, and the elevation in fig.

FIG. 266.



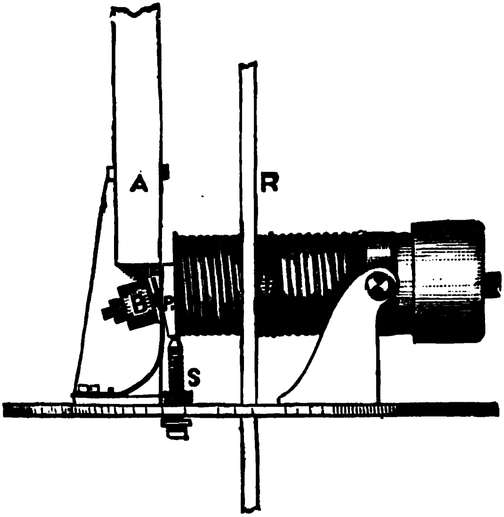
267. The regulation of the lamp is effected by an electro-magnet of the horse-shoe type, E, which is capable of rocking within certain limits, on the centres C C.

On starting the lamp the pole P attracts the iron rod R which carries the upper carbon, and holds it with a force proportional to the strength of the current flowing through the lamp ; at the same time the other pole, P_1, is attracted towards the fixed armature A, and the magnet moving upwards carries the upper carbon rod with it, and thus strikes the arc.

As the carbons are consumed the resistance gradually increases, and the current diminishing at a corresponding rate, there is less magnetic attraction towards the fixed armature ; the rocking magnet then falls to its original position of rest, supported by the stud S (fig. 267), and causes R to approach the lower carbon and so to maintain the arc, the current strength being at the same time increased proportionally.

As the consumption of the carbons is continued and the length of the arc therefore increased, the current is again diminished. With this diminution the magnetism is so reduced as to allow the carbon-holder R to slip until the arc reassumes its proper length, and the normal current is re-established, when the magnet is once more enabled to support the weight of the rod.

FIG. 267



In practice the rod is continually slipping by imperceptible degrees, and compensating exactly for the consumption of the carbons.

To avoid sudden jerks in the action of the rocking magnet, a magnetic brake B is employed, which introduces friction in inverse proportion to the length of the arc. The two carbon-holders are connected by a cord passing over a pulley wheel, so that the two carbons approach or recede simultaneously.

The lamp is constructed in various forms, but in all of them the same simplicity of parts is maintained. The globe is fitted to a pair of sliding rods and can be drawn down out of the way so as to expose the carbon-holders and facilitate the renewal of the carbons.

CHAPTER XVI.

INCANDESCENT LAMPS—PHOTOMETRY.

IT was shown when discussing the Cardew Voltmeter, that if a current of electricity is urged through a solid conductor, heat is developed, and that the amount of heat so developed is proportional to the total energy expended in the conductor. It was also shown that this energy is proportional to the product of two factors, viz., the strength of the current C, and the difference of potential E between the extremities of the conductor, necessary to maintain that strength—or the heat H developed is proportional to $E\,C$; but by Ohm's Law $E=C\,R$, therefore $E\,C=C^2R$.

It is manifest from these simple formulæ, that the heat developed varies directly as the resistance, and directly as the square of the current strength. It may also be said to vary directly as the potential difference. If we have two equal and uniform conductors A and B, and maintain a potential difference at the ends of one of them, A, twice that of the other, B, the heating effect will be quadrupled; for with equal resistances the current strength will also be doubled, and in fact energy is being expended four times as fast in A as compared with the rate of expenditure in B. If, however, while both conductors are of the same length and sectional area, the specific resistance of B is twice that of A, and the same potential difference is maintained in both of them, the resistance of B being twice that of A, will halve the strength of the current flowing through B. Hence if in A, $H = E\,C$, or C^2R, then in B, $H=\frac{1}{2}CE$ or $2R\left(\frac{C}{2}\right)^2=\frac{1}{2}C^2R$. In this case twice as much heat is developed and twice as much energy is expended in A as compared with B. Again, if the current in B is made equal to that in A, by doubling the potential difference in the former, then in A, $H=EC$ or C^2R, and in B, $H=2EC$ or $2C^2R$, so that doubling the resistance and keeping the current strength constant, doubles the heat developed and causes twice the amount of energy to be expended. One great lesson is here again enforced, viz., that the amount of energy obtained in the form of heat can only equal and never by any possible means exceed the amount of electrical energy expended or absorbed in the conversion.

The relation between heat and temperature has already been discussed, but we must again refer to it here, for it is of the utmost importance. Let us suppose that instead of employing a conductor of increased specific resistance, we experiment with two samples of the same material and of the same sectional area, but that one of them, B, is twice as long as A ; then the resistance of B will also be twice that of A, and if equal currents are urged through these conductors, the heat developed in A will be only half that developed in B ; but as B is twice the length of A and has therefore twice as much matter in it, the temperature of the two conductors will be equal. Now when a body is made very hot it becomes luminous, and the luminosity of a body is proportional to its temperature. In this experiment, therefore, the temperature of A and B being equal, the luminosity will be equal, although B absorbs twice as much energy as A, because its resistance is double. Now if the resistance of B is made double that of A by halving its sectional area instead of by doubling its length, and equal currents be urged through each as before, we still get twice as much energy absorbed, and therefore twice as much heat developed in B as in A. And since the mass, or the quantity of matter in B is now only half that in A, equal quantities of heat would cause the temperature of B to be twice that of A ; therefore as twice the amount of heat is developed in B, its temperature is raised to four times that of A. This clearly indicates the direction in which we should work in order to raise a conductor to a very high temperature. Stated generally, a large amount of energy must be expended on a small mass of matter; therefore the conductor must have a high resistance, and in order to keep its mass small this high resistance must be obtained by diminishing its sectional area rather than by increasing its length, and further, the material chosen should be one which has a high specific resistance.

Men were not long in conceiving the idea of employing the heating effect of a current upon a conductor for illuminating purposes, and patents based upon this principle were taken out nearly fifty years ago. But these early efforts were one and all of them failures from a commercial point of view, although some of them were identical with many of those of a comparatively recent date. It was seen that a conductor of high specific resistance was necessary, and this limited the number of materials available. This number was further reduced by the fact that most conductors either melt or volatilise at comparatively low temperatures—before, in fact, the temperature of white heat is attained. Iron, which is cheap and has a high resistance and which might therefore be considered a suitable substance, unfortunately melts at a comparatively low temperature. It is for this reason useless as an illuminant. It also oxidises or combines with the oxygen of the air as its temperature rises. German silver is for similar reasons not available. We are, indeed, limited among the metals to the expensive platinum or its alloys, unless we take into account the experiments which have been made with iridium, a most expensive and very scarce metal, and which, if equal to the requirements, could probably not be procured in sufficient abundance to meet the demand. Platinum is capable of being raised to a bright white heat, and can then emit light of dazzling brilliance. It has also the advantage of being practically inoxidisable. The critical temperature is, however, suddenly reached; that is to say, above a certain point, a slight increase of temperature suffices to produce liquefaction, and therefore to cause a rupture and so disconnect the circuit. It must also be remembered that the resistance of metals increases materially with an exaltation of temperature, a fact which hastens the fracture of the wire. Efforts have been made to prevent this overheating by means of automatic regulators, which short-circuit the lamp when the current reaches a certain predetermined strength, and so cuts off the current just at the moment that there is a risk of breaking the wire. Some of these are clever laboratory expedients, but nothing more. If, then, we had been restricted to metallic conductors, electric lighting by incandescence would long since have been given up as impracticable. Carbon, however, which is a non-metallic body, is a fairly good conductor of electricity, although of considerably higher specific resistance than platinum. A very remarkable feature pertaining to it is that its resistance decreases with an increase of temperature. It is a substance which cannot by any ordinary means be melted or volatilised (although a temperature has been attained at which it becomes flexible), so that in this respect it is superior to platinum or any other of the metals. It however oxidises readily when heated in an atmosphere containing free oxygen, such as ordinary air. This difficulty was for a long time insurmountable, although many efforts were made to overcome it, such as placing it under a glass receiver or shade, and depriving the enclosed air of its oxygen by means of a piece of phosphorus, a substance which oxidises readily at ordinary temperatures. In this case, the carbon is suspended in an atmosphere of the remarkably neutral or inactive gas nitrogen. But even such an arrangement as this was soon found to be clumsy, unsatisfactory, and in fact impracticable. Even supposing it to have been otherwise, the carbon procurable was very defective. Thin rods of graphite or gas-retort carbon such as is used in the Bunsen cell, or sections of the artificially prepared material such as is used in the Leclanché cell, were tried; they could not, however, be obtained of sufficiently small sectional area, and were too irregular in structure to prove practicably useful. Efforts were also made, and with a better prospect of success, to accomplish the object in view, by placing the carbon in the then best obtainable vacuum. The vacua were for a very long time far from perfect, and as a consequence the durability of the carbons was very brief, but when it was shown how it was possible to secure an all but perfect vacuum, a fresh impetus was given to the idea of lighting by the incandescence of thin pencils or, as they were subsequently called, filaments of carbon. Since then, the real improvements that have been made have been in the formation and fixing of these filaments, which can now be prepared from almost any substance having a large proportion of carbon in its composition. As organic substances consist to a great extent of carbon, and as these substances can generally be decomposed somewhat readily, it is only natural that they should form the basis from which the filaments are manufactured. Filaments as they are now made, can be divided into two classes, (1) those in which the fibrous structure of the carbonaceous body is retained, and (2) those in which the original or organic structure is altogether destroyed during the process of manufacture, and the material rendered thoroughly homogeneous. To the first class belongs the Edison lamp, and to the second class, the lamps of Swan and the majority of other inventors. It is a remarkable fact that Edison asserted in his patent that to give the carbon the highest possible resistance and the smallest tendency to disintegration, it should retain its structural character, and that such carbons alone possess these qualities, qualities which are impaired by any treatment tending to fill up the cells or pores with unstructural carbon, or to increase the density or alter the resistance of the fibre. Swan, on the other hand, maintained that the structure of the material should be entirely destroyed, and the carbon filament made as dense as possible. Although good and efficient lamps can be manufactured on either of these principles, experience seems to show that the latter or homogeneous filament is the better of the two.

In attempting to deal more specifically with the manufacture of incandescent lamps, we are met with two serious difficulties: the first is due to the enormous number of processes which have been introduced, but to the great majority of which the limits and purpose of this work will not permit us to refer. Legal decisions which have been given in recent actions between the various makers, have however considerably reduced the number and variety of processes actually in use. The second difficulty arises really from a kind of jealous fear, for the practical makers of lamps regard their methods as secrets which it is their bounden duty to keep religiously to themselves.

It might have been gathered from what has already been said that the chief desiderata in a good lamp are, (1) that the filament shall be sealed in an airtight vacuous glass vessel; (2) that efficient means shall be provided for connecting the filament with the external circuit; (3) that the filament shall offer considerable resistance; (4) that it shall have a small mass, so that its temperature shall be raised as much as possible by a given quantity of heat; (5) that it shall be durable at high temperatures in a vacuum; and (6) that the lamp shall be capable of being manufactured at a small cost, and of any desired dimensions or resistance. At present it is the last of these requirements which gives the greatest trouble in meeting, because a slight variation either in the thickness or sectional area, or in the amount of radiating surface of the filament, causes a considerable difference in the luminosity.

The filament in the Swan lamp is made either direct from cotton thread, or from a thread formed by squirting a solution of cellulose through a fine nozzle at high pressure, cellulose being the chief constituent of such vegetable substances as cotton, linen, paper, &c. The first process with the cotton is that of parchmentising it. This is no secret, the method adopted being the same as that for making ordinary parchment paper. A solution of two parts of sulphuric acid to one part of water having been prepared, the cotton thread (which should be of a loose texture such as knitting or crochet cotton) is wound on a drum, from which it is passed slowly through the acid solution. During the passage the acid acts on the fibres and gradually destroys their molecular structure, partially dissolving the material, and converting it into a gelatinous semi-transparent state, as cellulose, having a chemical composition of $C_6H_{10}O_5$. Having been brought to this condition it is passed over freely revolving rollers or pulleys into a bath of running water, where it is slowly and uniformly wound on to a large perforated metallic drum driven by machinery. When the drum is covered it is removed and placed in another water bath, to ensure a thorough washing. It is absolutely essential that every particle of acid should be removed, for were any left behind, it would on drying destroy the thread by dissolving it. After being thus thoroughly washed the drum is removed from the water and placed aside, to allow the thread to dry. When first placed in the washing bath it gradually loses its transparency, becoming white and opaque. But on drying, it returns to the transparent state, with the additional property of being remarkably tough, becoming a horny thread, with every trace of the original twist destroyed.

This process can be carried out in a small way, and is very instructive. A piece of knitting cotton is wound round a piece of glass, or better still, round a frame made of pieces of glass rod. It is then dipped into the acid solution of the proportions above mentioned. The process must be carefully watched, and if the action has been of just sufficient duration, but not lasting too long, the change from the fibrous to the homogeneous state will be readily seen. It should then be placed in water, well washed and dried. The drying is best performed by stretching the thread gently in a straight line, or if too lengthy, over a series of pulleys. If the thread is left in the acid too long, the solution is carried too far and the thread weakened, so much so as not to be able to bear its own weight even in a length of a few inches. The same thing happens if the thread on being removed from the acid is placed on a plate or piece of glass, instead of being at once immersed in the water; the acid remaining in the thread completes the dissolving process and liquefaction ensues. It is possible to remove the thread from the acid too soon, the defect then being that the destruction of its fibrous character is only partly performed.

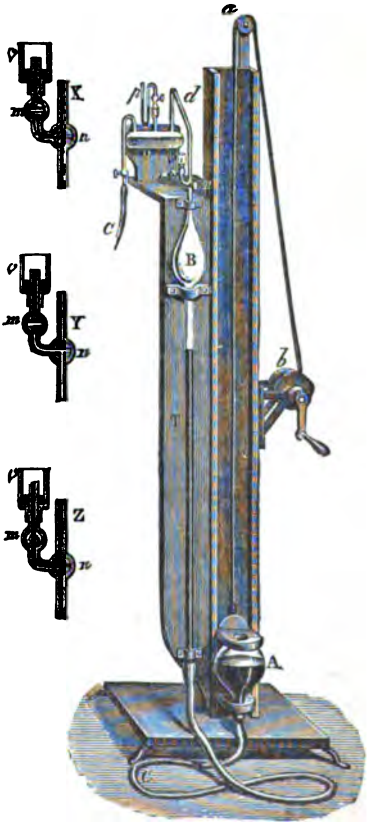
The thread having dried, it is next cut to a uniform gauge throughout, which is done by drawing it through a series of jewel dies decreasing slowly in diameter. It is then subjected to the process of 'carbonising,' or converting it into a solid carbon filament. The thread is first wound on a frame consisting of two round carbon or porcelain rods kept in position by being fixed into holes in two side-pieces. The round rods are sufficiently far apart to make each bend of the thread correspond to one filament, for it is in the process of carbonising that the filament is definitely shaped. In order to make the loop, which was at one time one of the characteristic features of the Swan filament, the thread is turned twice round one of the carbon rods in the frame before passing to the other rod. One object of this formation is to get a long filament in a comparatively small bulb. The frame having been filled, pieces of cardboard are placed on its sides or faces to prevent accidental injury to the threads, the whole being then wrapped round with paper. A number of such parcels is placed in a crucible or cast-iron box, until the vessel is nearly full. Powdered charcoal having been shaken over the contents to fill up any spaces that may have been left, the lid is placed in position, and an air-tight joint made with a little fireclay. As the powdered charcoal gets hot it absorbs any free oxygen that may be in the crucible and prevents any getting to the filaments; were it to do so, it would speedily destroy them. The crucible being thus prepared, is placed in a suitable furnace and raised slowly to a white heat. The gradual increase of temperature is important in determining the shapeliness of the filament. Too rapid an increase in temperature would alter the dimensions of the frame and cause the threads to sag, so that the form of the filaments would be more or less distorted. The high temperature is necessary to render the carbon hard and durable, to increase its conductivity, and to reduce its capacity for holding atmospheric and other gases within its pores. This last-mentioned feature is not only interesting, but it is also fraught with the utmost importance. All substances are more or less porous, and have the power in varying degrees of holding gaseous particles within those pores, a power or property known as occlusion. As the temperature of a body rises these gaseous particles expand and force themselves through the substance, frequently causing minute fissures ; with some substances which do not liquefy, such as carbon in its ordinary form, this power of occluding gases returns with a resumption of the normal temperature. It is, therefore, imperative that the nature of the carbon should be so altered as to prevent this taking place. Hence the necessity for thorough carbonisation at a high temperature.

This alteration in character of the carbon is continued in the next process, which is that of 'flashing.' Before proceeding with this process, however, the filaments are cut to about the desired length, sufficient margin being allowed for making connection with the platinum wires, which pass through the bulb to the external circuit. The filament is then held by a pair of clips connected with suitable terminals, by means of which a dynamo, or better still, a battery of secondary cells, can be joined on. The suspended filament is then placed in an atmosphere of some hydro-carbon, more generally ordinary coal-gas (which is rich in carbon), and traversed by brief currents sufficiently strong to raise it, or portions of it, to a white heat. The effect of this process is to partially decompose the gas, which is at the ordinary atmospheric pressure, and to cause a deposition of carbon particles on the surface of the filament. Should there be, as is generally the case, any inequality in the filament, causing a variation in its resistance, one portion will be raised to a higher temperature than another, and upon this hotter section a greater deposit of carbon will take place. The flashing process is therefore continued until the carbon assumes a uniform temperature, that is to say, until it becomes uniformly luminous throughout. The process also serves to reduce the power of occluding gases in the interstices between the particles. The filament is next placed in an exhausted receiver, and a continuous current passed through it, the result being that the carbon is hardened, the conductivity increased, and the power of occlusion eventually destroyed; but to bring about these results the temperature must be raised to a white heat, the current being maintained until the resistance is reduced almost to the required limit. The final flashing may, however, be reserved until the filament is fixed in the bulb and ready for finishing off. Platinum wires are always employed in mounting the filaments, as it is the only metal which has a coefficient of expansion nearly equal to that of glass; that is to say, it expands or contracts with variations of temperature at almost exactly the same rate as glass, so that it can be fused into that material without any risk of its subsequently fracturing the glass on cooling. The wires are first fused along the sides of a short piece of glass rod, or have a little molten glass twisted round them while they are held in position. In the former case, a piece of glass tubing is fused over the rod, thereby encasing the wires for a portion of their length. The connection with the carbon is made by flattening out the ends of the wires into minute plates, which are then bent gently round the ends of the filament, to which they are fixed with carbonaceous cement. The joint is completed by carbonising the cement by means of a strong current sent through it. Instead of using the cement, the joints are sometimes perfected by immersion in a hydro-carbon liquid or gas, the filament being short-circuited and the joints raised to incandescence by a strong current, causing a decomposition of the hydro-carbon, and a deposition of the carbon upon the joints. There are several other methods of mounting, but they are mostly based upon or are modifications of those above described.

The next process is that for exhausting the bulb of its contained air and moisture. This has to be performed carefully, and it is here that some of the greatest difficulties are met with.

The vacuum obtainable in an ordinary mechanical air-pump is, as we have already indicated, far from perfect, and useless for the purpose. There are, however, two types of mercurial air-pumps which are so far superior to the mechanical form that they can produce even higher vacua than are actually required for lamp-making. It is, of course, well known that if a long glass tube, say 36 inches long, sealed at one end, is filled with mercury and then inverted with its open end under the surface of mercury contained in a basin or other convenient vessel, the liquid metal in the tube will sink until its surface is about 30 inches above that of the mercury in the basin—until, in fact, just a sufficient height of mercury is left in the tube to balance the atmospheric pressure on the mercury outside. It follows that the space in the tube above the level of the metal is a more or less perfect vacuum, and it is generally known as a Torricellian vacuum, owing to the fact that Torricelli was the first to perform the experiment.

FIG. 268.

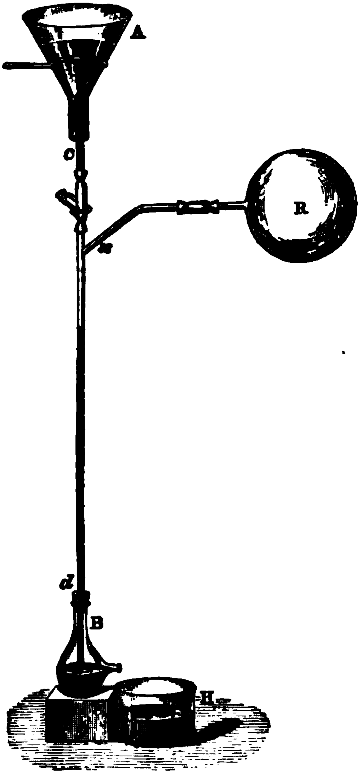


The Geissler pump, although but a modification of the Torricellian apparatus, is an instrument of incalculable value. A laboratory form of this pump is illustrated in fig. 268. A is a glass vessel or reservoir which is connected by a piece of flexible tubing, C, with a barometer tube, T, terminating, at its upper extremity, in a glass reservoir, B, which may be called the pump-head. The latter reservoir is connected to a three-way tap, *n*, of which enlarged views are given at X Y Z. When this tap is turned, as at Z, communication between B and the outer air at *v* is established, an additional ordinary tap being, however, interposed at *m*. When *m* is turned off, as at Y, communication with the outer air is shut off; but if *n* is turned into the position shown at X, the pump-head is connected to the tube *d*, which leads into the drying tube *e*, containing sulphuric acid. The receiver or other vessel to be exhausted is connected to the tube *c*, which also leads into the drying tube. A small manometer or pressure gauge, *p*, also communicates with *o*, and serves to indicate the degree of exhaustion obtained. The reservoir, A, has a cord attached to it, which, passing over the pulley, *a*, is fixed to the drum, *b*. By means of the handle attached to this drum, the reservoir can be raised or lowered through a distance of nearly 4 feet.

If now A is placed at the top of its range, the taps *n* and *m* being open as at Z, the mercury on being poured in will fall down the tube C and rise in T until the pump-head, B, is full, or until the mercury columns in the two tubes are balanced. The air in T and B will, of course, be expelled at *v* as the mercury rises in the tube. Supposing the taps to be next turned so as to shut off communication with the outer air and connect B with the receiver or incandescent lamp bulb which is to be exhausted, and then the reservoir, A, to be lowered sufficiently, the mercury will flow out of B and down T until it is just balanced by the pressure of the air on the surface of the mercury in A. The air in the receiver or bulb then expands uniformly so as to occupy the space in the pump-head and tube above the mercury. The tap *n* is again turned so as to shut off the receiver. On raising the reservoir, A, the mercury again rises into B, and the taps being turned so as to open communication with the atmosphere, the contained air is driven out. This done, *n* is once more turned so as to open communication between the receiver and B, and cause the air left in the receiver to again expand when A is lowered. This air is in its turn expelled, and the process repeated. The operation is obviously a very slow one, although it is possible with this apparatus to obtain very high vacua.

The other type of mercurial pump to which we have referred is the Sprengel, the fundamental principle of which is illustrated in fig. 269. It consists of a stout glass tube, *c d*, 39 or 40 inches long, with a branch *x* connected to the vessel R to be exhausted. A large funnel-shaped reservoir, A, supported by a stand, is connected to *c d* by means of a piece of india-rubber tubing, the size of the channel through it being adjusted by means of a pinch-cock. The lower end of *c d* dips below the surface of the mercury in the flask B, which is furnished with a spout a little higher than the bottom of *c d*, in order to allow the mercury to pass out into the reservoir, H. The pinch-cock is so adjusted as only to allow the mercury to pass down the shaft a drop at a time. Each drop constitutes a plug or piston which fits closely to the sides of the glass and in its descent drives before it any air that may happen to separate it from the drop beneath it. The shaft *c d* is to all intents and purposes a barometer, so that the drops of mercury accumulate until a column is formed about 30 inches high, the actual height depending upon the counter-pressure of the outer air at the time being. Hence the distance which the mercury pistons ultimately fall is only 9 or 10 inches It will be evident that as the drops fall, and tend to establish a vacuum above them, the air in R expands and part of it occupies this otherwise vacuous

FIG. 269.



space. Consequently as each piston passes the junction of x, the air is swept out little by little until finally a very good vacuum is obtained in R. When the degree of rarefaction becomes considerable, the pistons fall smartly upon the column of mercury and give out a distinct metallic ringing sound. This hammering frequently sets up such strong vibrations as to fracture the glass; and it is this which really limits the length of the shaft. As the mercury falls on the barometric column, an equal quantity is, of course, driven out at the lower end, carrying with it, also, the bubbles of air which separate the little plugs. The mercury collected in H is replaced in A as necessity arises. This process is also very long and tedious.

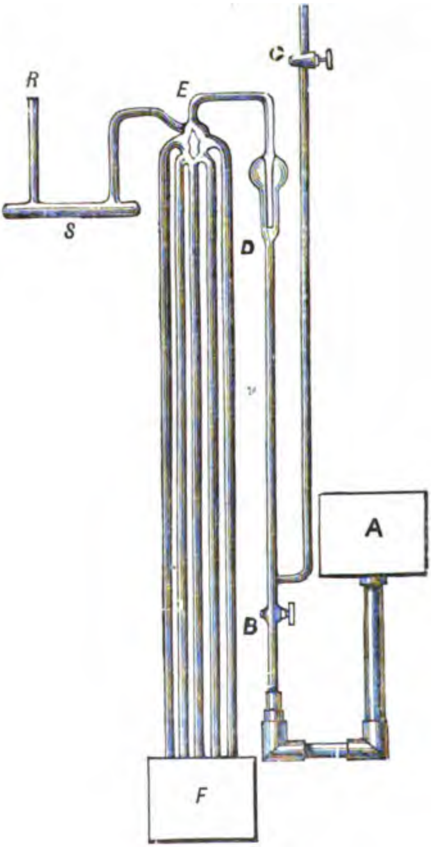
The exhaustion can be materially hastened by employing a good mechanical air-pump to exhaust the system as far as possible by mechanical means, the process being afterwards completed with the mercury pump. A simple barometer gauge can also be used to indicate, by the height of its contained mercury, the degree of exhaustion obtained.

These are the two systems of pumps upon which the apparatus actually employed in exhausting incandescent lamp bulbs is based. These simple forms are, however, open to many serious objections. A film of air always attaches itself to the surface of glass, and at times some difficulty is encountered in getting rid of it. Air is also supposed to be confined in the mercury itself, but there is some doubt on this point. To get rid of other impurities the mercury should always be distilled, and never allowed to get dirty by contact with brass or any other substance which it is likely to attack. Ordinary air always contains more or less moisture, and to get rid of this the air as it is exhausted from the lamp bulb is made to pass through sulphuric acid or phosphoric anhydride in order to dry it before it is allowed to enter the pump. Grease used for lubricating taps is also injurious for similar reasons, and should, therefore, be avoided. Taps themselves are serious offenders. No matter how perfectly they are made, they must allow some air to enter the pump, more especially when high vacua are obtained, and when, therefore, the pressure of the outer air on the tap is very considerable. To overcome this difficulty, taps are now superseded in the essential portions of the pump by small glass valves moving up and down in the pump as the mercury rises and falls. Their ends are ground to fit the seating, the passage being effectually sealed by a small ring of mercury which is retained as the valve drops into position. One of these valves is shown at D in fig. 272.

But mercury, like other bodies, is more or less volatile, and when the exhaustion in the pump is carried beyond a certain point, the exceedingly small pressure on the mercury surface permits vaporisation to take place. Although the degree of exhaustion of incandescent lamp bulbs is comparatively low, and not sufficient to cause any considerable amount of vaporisation, it may be interesting to mention a device by Mr. Crookes for keeping the vapour out of the receiver to be exhausted. Between the receiver and the pump he placed a long tube containing in the middle of it a little iodine, on each side of which was placed powdered sulphur. The mercury vapour was arrested by the iodine and converted into solid iodide of mercury. The iodine, which is itself volatile, was prevented by the sulphur from getting out of the tube either way, by its conversion into iodide of sulphur. But there was also a risk of the sulphur getting out of the tube, and this was prevented by placing in its path powdered silver, which, combining with sulphur vapour, would form sulphide of silver. In this way it would be possible to prevent any mercury passing into the receiver, which would, therefore, contain nothing but the exceedingly minute residuum of air.

One of the most practical forms of pump is that of Mr. Gimingham, the factory type of which is illustrated in fig. 270. A large vessel, A, is employed to supply several pumps, the flow of mercury through each pump being regulated by the tap, B. The mercury is driven up the tube D and enters the pump-head at E, where the drops are divided between five Sprengel fall-tubes, carrying with them the air from the lamp bulb attached to R, which on its way to the pump passes through the horizontal drying tube S. The mercury plugs fall into the reservoir F, whence the metal is lifted by a force-pump into A again. But as the mercury is very liable to carry with it minute air-bubbles, which would be given up in the pump and impair the vacuum, some device becomes necessary for arresting these atmospheric particles. The bubbles usually find their way to the surface of the glass, and slide upwards with the mercury. This fact permits the adoption of a very simple but effectual form of 'air-trap,' as shown near the top of the tube D. The tube is at this point enlarged to a bulb, through the top of which is fused the tube leading to E. This inner tube is open at its lower end, which is clear of the outer tube, so that the mercury on rising passes freely through it on its way to the pump, while the air-bubbles continue their course along the surface of the glass, and are consequently arrested or trapped in the upper part of the bulb.

FIG. 270.



A more elaborate form of the same pump is shown in fig. 271, for which we are indebted to the Council of the Society of Arts.

The supply vessel *a* communicates by a long flexible tube with a forked tube *c*. The tube on the left, which is controlled by the pinch-cock *r*, leads through two air-traps, *n*, *m*, to a McLeod pressure gauge, an appliance used for measuring the pressure in very high vacua where the ordinary means of measurement are not available. The process consists in compressing a large but known volume of the rarefied air into a comparatively small space also of known dimensions, and then measuring the pressure under the altered conditions. The tube on the right, controlled by the pinchcock *q*, leads through the air-traps *h*, *i* to the pump-head, where the mercury divides between the five fall-tubes, which are about 39 inches long, and which discharge into the capacious reservoir shown at the bottom. The tube *t* is the exhaust tube, having three branches, one, *s*, leading to the McLeod gauge, another, *l*, to the barometric gauge, *u*, and another through the drying and absorbing tubes, *x* and *y*, to the lamp bulb. A comparison barometer is placed at *w*. The supply vessel A is lowered from time to time and communication established

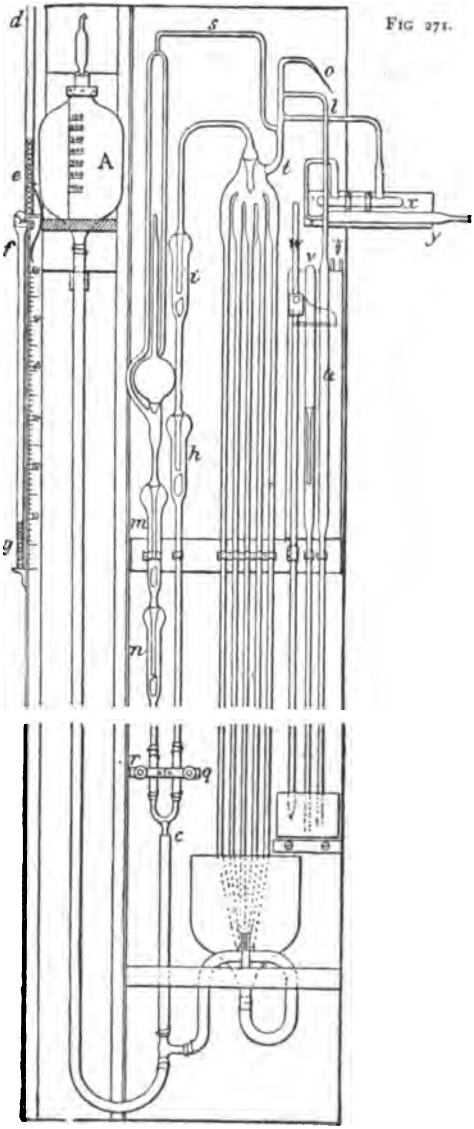


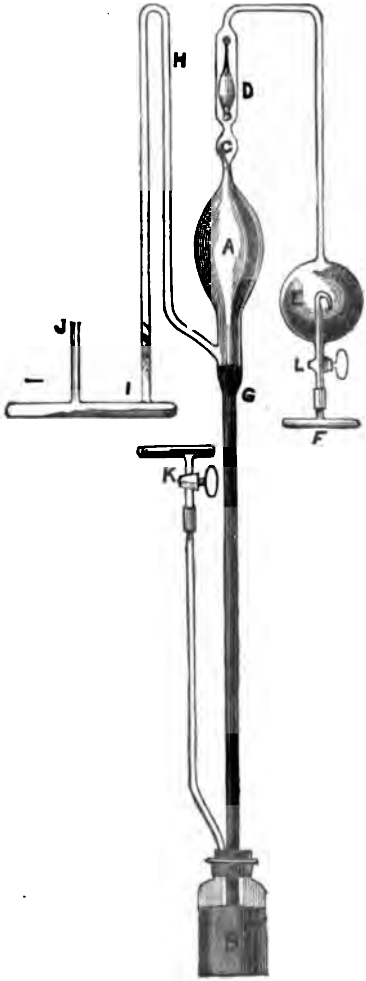
FIG 271.

with the collecting vessel so as to allow the mercury after it has passed through the pump to refill it. In experimenting it is sometimes necessary to count the number of times this vessel is raised; this is done automatically by the tubes *d e* and *f g* with the aid of a few leaden shot, one shot being made to fall from the upper to the lower tube every time the vessel A is raised. Mr. Gimingham has experimented very extensively with mercurial pumps, and finds that 39 inches is the best length for the fall-tube. He says that 'An experiment recorded in my note-book with a five-fall tube pump whose tubes were at first made 33 inches long, and then were lengthened to 39 inches by sealing pieces to their lower ends, shows that by passing the same quantity of mercury through at the same rate, a certain globe was exhausted in the first case to 50 mm. pressure, and in the second to 1 mm., showing a great increase in the rate of exhaustion, due to the extra 6 inches of fall-tube. On the other hand, if they be made of a greater length than 39 inches the fall of the mercury at the high exhaustion causes such severe hammering that the tubes are liable to be fractured.'

From other experiments he deduced that in the higher stages of the exhaustion, the air particles, instead of being swept out by the pistons, are taken out by a process of entanglement with the mercury.

Mr. Swinburne has invented an exceedingly simple and useful pump (fig. 272). It consists of a bulb, A, on a long shaft, G, which passes through an air-tight stopper nearly to the bottom of the bottle B. The bulb is drawn to a point at the top, and the tube is enlarged into a little bulb at C. It is again contracted where it joins the valve tube D. From the top of D there is a tube to the globe E communicating with the tube F, which serves for a number of pumps and in which a vacuum is maintained by a mechanical pump. H leads to the drying tube I, and J to the branch tube on which the lamps are sealed. The pump is started by opening the tap L, but the bent tube leading into the globe E is drawn very fine so that the exhaustion takes place gradually. The bending in this tube prevents any globules of mercury that may be drawn over into E from getting into the vacuum tube F. When the vacuum in the pump and lamps has been brought to about half an inch, communication with F is cut off by turning the tap L, and the tap K is opened, and a higher vacuum developed by subjecting the mercury in B to alternations of ordinary atmospheric, and high air pressure. The height of the mercury shown in the shaft G is that due to the ordinary atmospheric pressure in B, so that when the high-pressure air descends through K, the mercury is driven past the opening of the tube H, through the bulb or pump-head A, through C and half way up the tube D. The extra pressure being now removed from B, the mercury descends, the valve in D closing the opening into C before it has all fallen so that the valve is sealed by the mercury. The mercury continues to fall till it reaches the level G, whence a further exhaustion by expansion from the lamp bulbs takes place. This small quantity of air is in its turn expelled, and the Geissler action continued until the necessary degree of exhaustion has been obtained. The little bulb C is introduced to prevent the mercury rising and hitting the valve smartly when the exhaustion approaches completion. Were it allowed to do so the air would probably be driven against the side of the glass and stick there. It will be evident that, as the passages both above and below D are exhausted, a very small pressure will suffice to raise the valve.

FIG. 272.



Reverting to fig. 269, it will be apparent that if the atmospheric pressure in B is reduced the mercury column in the shaft *cd* will be shortened, whence a shorter shaft will suffice. In pumps of this pattern recently devised by Mr. Stearn, there are three fall-tubes, each 10 inches long, completely enclosed in a partially exhausted chamber.

Such pumps are finding considerable favour, but they introduce a further risk, for, if anything happens to interfere with the partial vacuum, the mercury will be driven up with considerable force and get into the upper parts of the pump, possibly breaking it.

Many suggestions have been made to heat portions of the mercury pump with a view to hastening its action, and pumps have been constructed to suit this purpose, but they do not seem to have met with much success in practice. Vacua can now be obtained far in advance of the actual requirements, the most perfect vacua being developed by the absorption of the residual gas after the exhaustion has been pushed as far as possible by the mercury pump. This is done either mechanically or by using some substance with which the air particles combine chemically. Dewar has produced a vacuum, which he estimates at $\frac{1}{350}$ of a millimetre, by heating charcoal to redness in the vessel exhausted by the Sprengel pump.

Mr. W. Crookes says he has obtained a vacuum of one-hundredth of a millionth of an atmosphere, which is equivalent to one-tenth of an inch at the top of a barometer tube 200 miles in height. That would appear to be an almost perfect vacuum; but such is the smallness of the molecules of matter, that, were a small tube containing a centimetre of air exhausted to that extent, there would still be left in it ten billion molecules.

Although it is, evidently, a comparatively simple matter to obtain the degree of exhaustion necessary for incandescent lamps, there are several causes for a deterioration manifesting itself in the vacuum after the finished lamp has been laid aside for a time, such as the occlusion of gases by the carbon and platinum, and by the cement employed to connect them together, and the very thin film of air which is liable to adhere to the inner surface of the bulb. In order to expel these gases, the filament is raised to incandescence during the later stages in the process of exhaustion, or the heat is applied externally.

The lamp having been sufficiently exhausted, the small glass tube connecting the bulb to the exhaust tube is fused, drawn out to a thread, and the lamp sealed off.

It remains now to test its efficiency, that is to say, the amount of light emitted for a given electrical power. A lamp may be said to have a very good efficiency if it yields one candle-power in return for 3·5 watts, so that an average 16 candle-power lamp should absorb 56 watts.

The vacuum is usually tested by means of an induction coil; one method is to fuse two platinum wires into a glass tube leading to the lamp, and simultaneously exhausted with it, and to connect these wires to the terminals of the secondary coil. The distance between the ends of the platinum wires inside the tube is so adjusted that when the required degree of exhaustion is attained, the spark passes through the air outside the tube, in preference to traversing the vacuous space between the platinum points. Another method applicable to the finished lamp is to connect one end of the secondary to the filament, and the other to a loop wound outside the bulb, the quality of the vacuum being determined by the relative feebleness of the discharge which takes place between the filament and the bulb. It should be observed that, in a badly exhausted lamp, not only does the filament 'burn,' that is oxidise, but it also requires a greater amount of heat to raise and maintain its temperature at the required point, owing to the fact that the air particles carry a portion of the heat away by convection.

The 'life' of an incandescent lamp or the number of hours that it can maintain illumination varies considerably. Some filaments fracture in a few hours, while others will last for years, and we have seen one which had been burning steadily for at least 8,000 hours, and at a good efficiency. It will be obvious that the life of the filament must in a great measure depend upon the strength of the current which is sent through it. If a comparatively feeble current is employed the lamp will last much longe than it would with an abnormally powerful one. On the oth hand, the luminosity increases much more rapidly than the curre strength, so that the question really resolves itself into one of comparative expense. A lamp that is burning low yields a much lower efficiency, but lasts longer, than one of the same type which is brilliantly illuminated; but it may be accepted, generally, that it is more economical to run lamps at a high than at a low efficiency.

The filament of the Edison lamp, which is, however, rarely used now, is made from bamboo, which is carefully cut into very fine strips of the required length, provided with little enlargements at the extremities to facilitate the fixing to the platinum wires which are fused through the bulb.

The carbonising and subsequent processes are similar in principle to those already described, the method of fixing the carbon to the platinum being, however, somewhat different. The flat ends of the carbon are mechanically gripped by the platinum, and the junction is made electrically perfect by a small coating of copper deposited electrolytically,—that is to say, the joint is connected to the negative pole of a battery and is then placed in a bath or vessel containing a solution of copper sulphate, in which is immersed a copper plate connected to the positive pole of the battery. As the current passes through the solution, copper particles are dissolved off the copper plate, and an equal number of particles precipitated upon the joint. Electrical continuity is in this way ensured, but during the subsequent working of the lamp there is a tendency towards the disintegration of the copper, which is sometimes deposited upon the inner surface of the bulb as a thin metallic film.

.Such are the general features pertaining to the construction of the Swan and Edison lamps; but the commercial interests in them have been amalgamated, and the distinction between them is therefore less marked than formerly, the Edison lamp pure and simple being now obsolete in England.

For ordinary purposes the filaments of the Edison-Swan lamps are shaped either as single or double loops. There are, however, several ways in which connection is made between the lamp and the external circuit, involving a corresponding variety in the form of the lamp-holders.

Figs. 273 to 275 illustrate the methods more generally employed for connecting the filament to the external circuit. In one of the lamps, fig. 273, the outer ends of the platinum leading wires are simply bent into small loops, the class of holder used being provided with two spiral springs connected to the circuit leads. The free ends of the springs are passed through the lamp loops, the shoulder of the lamp fitting into the circular part of the brass strip, the straight portion of which is just long enough to keep the spirals extended and so to make good electrical connection.

FIG. 273.

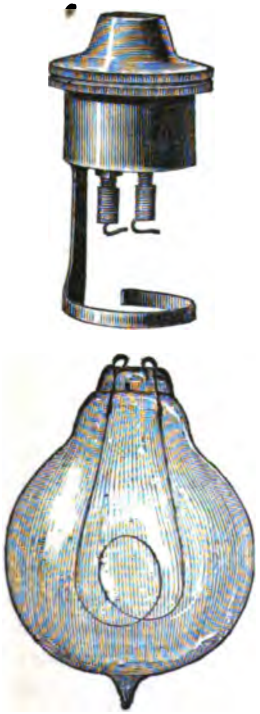
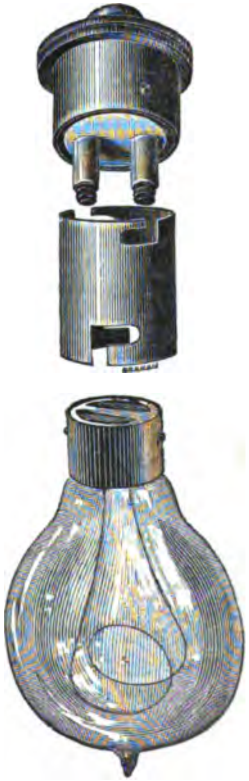


FIG. 274.



The top of the lamp shown in fig. 274 is provided with an insulated brass collar fixed with cement, the filament being connected to the two brass segments embedded in the cement. The collar has two small pins, which fit into the 'bayonet-joint' holder, which is shown in the figure, with its two parts separate. In twisting the lamp into the holder the segments make rubbing contact with the two spiral springs, which project a little from the guiding tubes. These spirals are connected to the circuit leads, and the lamp is thus thrown into circuit, by the mere act of fixing it in the holder.

FIG. 275.

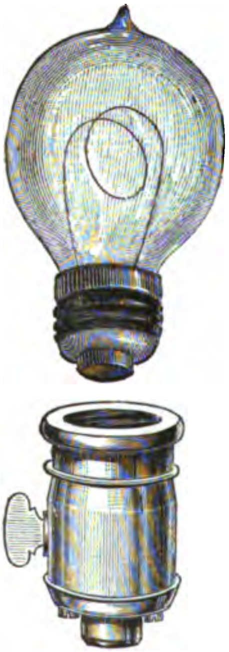
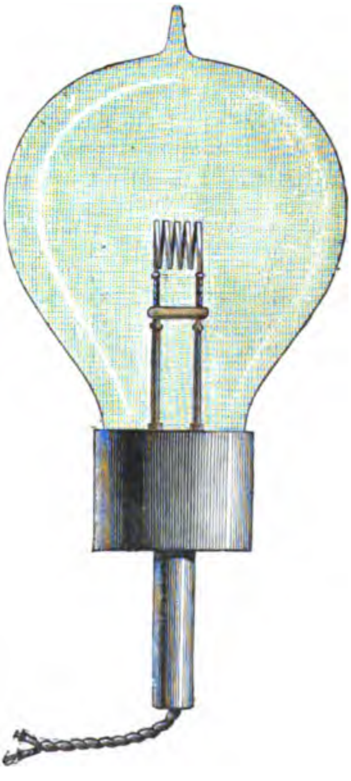


Fig. 275 illustrates the connection known as the Edison screw, in which one end of the filament is connected to the coarse screw thread, and the other to the insulated brass stud projecting from the bottom of the lamp. This affords another means of throwing the lamp in circuit by the act of placing it in its holder, which is provided with a corresponding brass screw thread, and a small brass disc mounted on a spring, which maintains contact with the stud on the lamp.

Lamp-holders are sometimes provided with small switches for making and breaking the lamp-circuit, the switch action being generally controlled by a tap handle similar to those used for gas-burners. In the Edison socket, as made by the Walsall Electric Co. (fig. 275), the tap carries a cam, which works against the curved edge of a brass strip, causing a to-and-fro movement of the spindle which, in the position for lighting, presses a brass spring against the stud on the bottom of the lamp. It releases with a snap action. Lamp-switches are, however, more generally independent, and fixed in convenient positions on the wall, &c., and one or two forms of them will be described in the following chapter.

Fig. 276 illustrates a form of lamp designed to overcome a difficulty experienced hitherto when using incandescent lamps for optical lanterns, as well as in other cases where the source of light should be small and approximate as nearly as possible to a point. The shape of the filament is that of a flattened spiral, forming a square grating constructed so that when fully incandescent it produces a square of intense luminosity, the light from which is wholly gathered up by a condensing lens in the focus of which the lamp is placed, and gives a perfectly uniform disc of light. This would not be the case if an ordinary incandescent lamp were used.

FIG. 276.



The lamp is mounted in a brass collar, with a shank to it, through which passes a flexible cord for leading the current to the lamp. A convenient holder is also made for the shank to fit into. It is provided with a set screw, by means of which the lamp may be varied in height or turned round; the holder is made with screw holes for screwing on to a block, or it may be soldered to the metal bottom of the lantern.

The lamp is made in two sizes (*a*) 35 to 55 volts, giving about 50 c. p. (*b*) 80 to 100 volts, giving about 100 c. p.

Incandescent lamps of the ordinary type are also made of high illuminating power, equal to that of 200, 500, and 1,000 candles. These lamps are suitable for interior lighting in public buildings and factories, and in other situations where a powerful and steady light is required.

In proportion to their actual c. p., these lamps are more economical to instal than groups of small incandescent lamps;

for example, the 200 c. p. lamp gives a light equal to 12 or 13 lamps of 16 c. p., but costs only twice as much as a 16 c. p. lamp, although the expenditure of energy per candle-power is in each case about the same.

These high c. p. lamps are fitted with strong brass terminals, and a special form of holder, which supports the lamp at the neck, takes the strain off the terminals, and can be readily adapted to any form of fitting, being provided with a screw thread of standard pitch—usually 1 inch male gas thread.

The following table supplied by the makers is interesting as showing the approximate E.M.F. and current required for the various classes of Edison-Swan lamps :—

1	candle-power	from about	3	volts &	·8	amperes	to about	8	volts &	·3	amperes
2½	,,	,,	5	,,	1·4	,,	,,	25	,,	·45	,,
5	,,	,,	5	,,	3	,,	,,	65	,,	·35	,,
8	,,	,,	10	,,	2·8	,,	,,	120	,,	·3	,,
16	,,	,,	15	,,	3·7	,,	,,	160	,,	·4	,,
25	,,	,,	40	,,	2·2	,,	,,	120	,,	·7	,,
32	,,	,,	50	,,	2·3	,,	,,	120	,,	·9	,,
50	,,	,,	50	,,	3·5	,,	,,	120	,,	1·4	,,
100	,,	,,	50	,,	7	,,	,,	120	,,	2·9	,,
Micro and Miniature Lamps		,,	3	,,	·8	,,	,,	8	,,	·3	,,

All lamps taking less than ·9 ampere are marked at 4 watts per candle, and all lamps taking more than ·9 ampere at 3·5 watts per candle. It is of course optional for consumers to run the lamps at higher efficiencies, if under the circumstances they consider that the higher efficiency compensates for the shorter life. Assuming an efficiency of 3·5 watts per candle, it follows that 746 watts, or one electrical horse-power, expended in the filaments would produce a light of 213 candle-power, an equivalent to that of thirteen 16 candle-power lamps. But the power developed by the dynamo is frittered down by the resistance of the leads, &c., so that, in practice, not more than ten 16 candle-power lamps can be maintained per horse-power generated.

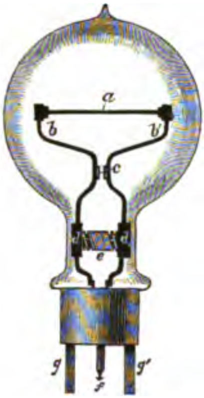
Lamps are sometimes silvered over one half of the bulb when the light is required to be reflected in one direction instead of being distributed all round. But in this case, the plane of the filament should always be placed in a line with the object it is sought to illuminate, as the light obtained from the lamp is always greater in that direction than in the direction at right angles to the plane of the filament. Artistic effect is also sought by colouring the bulbs to suit the surroundings, although this involves a loss of light, as certain of the rays are absorbed by the glass, the actual percentage so lost being governed by the particular colour employed. This absorption is altogether independent of the loss caused by the density or opacity of the material.

The Edison-Swan lamps are as a rule only made for parallel working, that is to say, they are all joined across the same pair of leads or mains, so that the current from the dynamo or other source divides between the various filaments. Of course it is possible to join two or more lamps in series, but under such circumstances the fracture of the filament in one lamp involves the extinguishing of the other lamp or lamps in series with it. If, therefore, all the lamps in a circuit were joined in series, the failure of one lamp would result in a total disconnection of the circuit. The parallel system has many advantages. There is no risk of receiving a serious shock on touching the mains, as the total potential difference is only that necessary for one lamp, which rarely exceeds 100 volts or thereabouts. If one of the branch leads should become broken, only the lamp on that branch will be thrown out of use. The means available for connecting the lamp to the supply wires are of the simplest description. The insulation of the mains is a matter of less difficulty than with high potential circuits.

On the other hand, the cost of the mains in a large installation is very considerable, for large conductors must be employed, otherwise their resistance would be so high as to cause a serious waste of electrical energy in overcoming that resistance. It needs also to be added that the maintenance of a constant potential difference throughout an extensive network of wires is a matter of some difficulty, a difficulty which does not attend series working.

The best lamp yet constructed for series or constant current working is probably that of Mr. Alexander Bernstein. The filament is composed of a slender carbon tube, made by carbonising a silk braid of fine texture, and it is remarkable that the fine threads composing the braid are distinctly discernible in the finished filament. Fig. 277 illustrates the construction of the lamp in which the straight carbon tube or filament *a* is supported by pieces of iron wire $b\ b_1$, their lower extremities being connected to the short pieces of platinum fused through the bottom of the bulb. These wires, $b\,b_1$, are bent in such shape as to almost touch each other at *c*. They are also furnished with sleeves of insulating material $d\,d_1$, connected together by a spiral spring *e* which strives to draw them together. As long as the carbon is intact, its rigidity prevents contact between *b* and b_1 at *c*, but as soon as a flaw in the carbon appears the current commences to destroy it, and the spring *e* gradually draws the wires together, until a perfect contact is produced at *c*, and then a short-circuit is obtained inside the lamp. It will thus be seen that this is an excellent device for series working, for on the extinction of one lamp by the fracture of its carbon, the circuit for the other lamps is automatically completed.

FIG. 277.

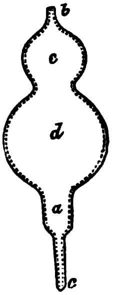


In a form of lamp now being introduced the spiral spring is dispensed with, a portion of one of the iron wires being hammered out flat, and a slight springiness imparted to it so that on the carbon being broken continuity is established at *c*.

The manufacture of the bulbs for 'loop' lamps is comparatively a simple matter, but with lamps having a rigid rod or tube such as the Bernstein, the case is very different. This will be evident when it is observed that the length of the carbon is considerably greater than the diameter of the neck of the bulb; with the ordinary bulb, the insertion of the mounted carbon would be a matter of impossibility.

The method of making the Bernstein bulb is very ingenious. Two bulbs, *e*, *d* (fig. 278), are first blown in a piece of glass tubing *b c*; the end *b* is then broken off, and the bulb *e* being heated it is worked into the form of an open cylinder. The carbon and the connecting wires, fixed in a glass stem, are then introduced through the large opening thus made, this opening being then closed so that only one bulb remains. The next operation is to weld a piece of small tubing to the top of this bulb, after which the small tube *c* at the bottom is broken off, and the stem with its connecting wires dropped through and fused into position. The next performance is to exhaust the lamp by way of the little tube fused on to the top, and that being completed, the bulb is sealed off and fixed into its socket.

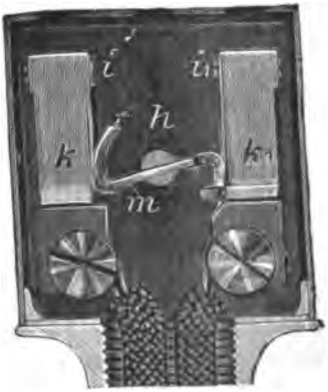
FIG. 278.



In order to prevent the interruption of the circuit by the removal of a lamp, its holder is constructed in such a way that the lamp can only be withdrawn from it if a short-circuit has been made in the holder beforehand; and, furthermore, as this short-circuit can only be broken after the lamp has been placed in position, it is not possible to disconnect the circuit at the holder.

This holder is shown full-size in figs. 279 and 280. A plate of insulating material, *h*, serves for the support of two metal sleeves, *i* and i^1, which are made suitable for the reception of the two square pins, *g* and g^1, of the lamp cap (fig. 277). For the purpose of obtaining a good contact between the pins and the sleeves, the outward side of each of the latter is cut away and replaced by two flat springs, *k* and k^1. The conducting wires are attached to the lower ends of the sleeves. The S-shaped piece, *m*, which can be turned by means of an external handle, serves the purpose of making a short circuit in the holder.

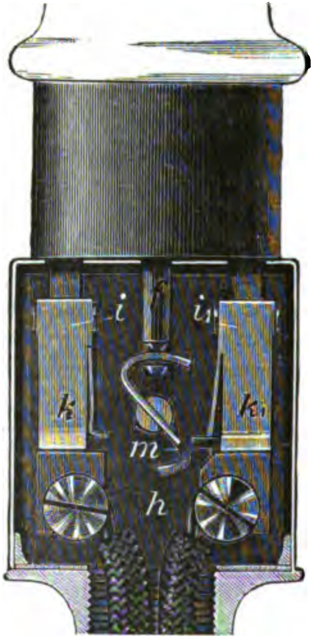
FIG. 279.



In fig. 279 the position of short circuit is indicated. For the purpose of obtaining a good contact between the piece *m* and the metal sleeves *i* and i^1, the latter are provided with two other flat springs, of which the one on the left side, near *k*, is bent at right angles at its lower end. The spring near k^1 carries at its lower end a square pin, which prevents the turning of the piece *m* in the other direction. The S-piece being thus fixed the circuit cannot be opened.

But if a lamp is placed into the holder, the two springs are slightly pressed outwards, and the square pin is forced out of the region of the motion of *m*; therefore *m* can be turned into the position shown in fig. 280, and in this case the current will pass through the lamp. It will be observed that the lamp cannot be moved out of the holder when the current is turned on, because the S-shaped piece *m* prevents the withdrawal of the lamp-cap by engaging with the peculiarly-shaped pin, *f*.

FIG. 280.



If it is desired to remove the lamp, the piece *m* must first be turned in the short-circuiting position shown in fig. 279.

The electro-motive force required by the lamp ranges from 4 to 15 volts according to the luminosity, which usually ranges from 16 to 50 candle-power. The normal current strength required is 10 amperes. On account of the small mass of carbon in the hollow filament, these lamps are very efficient and it is claimed that with lamps of from 32 to 50 candle-power, the consumption of electrical energy is at the rate of only 2·75 watts per candle.

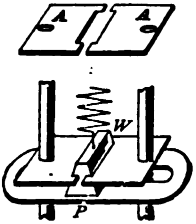
Lamps constructed after the principle of the Bernstein, that is to say for constant current, can also be joined up in circuit with ordinary arc lamps, which is, under some circumstances, a decided advantage.

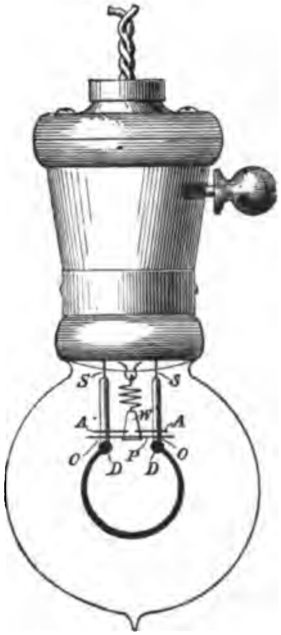
In cases where an arc lamp would give, at times, more light than is required and therefore waste energy, but where total darkness is undesirable, the Bernstein lamp is useful, as it can be joined, with the arc lamp, to a 'three-way' switch, by turning which either the arc or the incandescent lamp can be thrown in circuit, the current required for each being about the same.

When an ordinary incandescent lamp is used on a high potential circuit, a fracture of the filament sets up a small arc, which being sustained consumes the materials of the lamp and a disconnection is the result.

Mr. Edison in his 'Municipal' lamp has taken advantage of this feature to bring into circuit automatically a short-circuiting piece placed in the collar of the lamp. It is highly ingenious in design, and appears to answer when the fracture of the filament takes place during the time that the lamp is alight, but it is useless when the fracture takes place during the day, or at any time when the current is not passing, the E.M.F. being never sufficient to *initiate* an arc. Bernstein's plan is, under such circumstances, more satisfactory, although even here no provision is made against the mischievous stone-thrower or against any violent damage which might be done to the lamp. Accidents do happen which break the bulb and bend one or both of the iron wire supports and so prevent the short-circuiting at *c* (fig. 277) being effected.

FIG. 281.





Mr. A. A. Goldston has, however, devised a cut-out which acts promptly when the breakage is caused by any electrical or mechanical means. The device is illustrated in fig. 281, which shows the lamp, and an enlarged view of the cut-out. The leading-in wires, S S, are springy pieces of platinum and are connected to thicker pieces of iron wire, to whose lower ends, D D, the carbon loop is attached. Two small plates of German silver, A A, are rigidly fixed to the iron wires; below these is another plate, P, which carries a porcelain wedge, W, and is supported by a spiral spring, as shown. This plate has two slots, O O, through which the iron wires pass without touching. So long as the filament remains intact, it presses D D together and causes the wedge to be kept down by the pressure of A A. Should the filament be damaged, the tension at D D is released, the pressure of A A removed, and the spiral spring allowed to act. The wedge is then pulled up, and the plate P placed in contact with A A, thus short-circuiting the lamp.

There is another lamp, known as the Cruto, the filament of which is ingenious in construction and promised at one time to be successful. It consists of a fine carbon tube, made by depositing carbon from an atmosphere of coal-gas or other hydrocarbon, upon the surface of a platinum wire, which is heated by an electric current. When sufficient carbon has been deposited, the current strength is augmented and the platinum wire fused out more or less perfectly.

Incandescent lamps are serviceable in a variety of ways. For domestic lighting they, although in most cases in England somewhat more expensive than gas, know no equal. They in no sense of the word vitiate the air, nor do they consume it; they have very little effect upon the temperature of a room; they are not injurious to furniture, books, or ceiling, and deposit no soot; they can be placed in curtains or other combustible materials without entailing any risk of fire; they are independent of air currents which cause flickering in any lamp where gas or oil is burned; they are exceedingly convenient and can be 'turned on' at any moment without necessitating the use of a match; the tap or switch for turning them on can be placed in any convenient position, such as on a door-post; and the lamps are incompetent to cause explosions, because the filament is destroyed immediately the bulb is broken. On the other hand, they consume a practically invariable amount of energy, for the light cannot be turned down without the introduction of a shunt, or of resistance, in which the energy which would otherwise be developed in the lamp is expended. They are, however, bad for street lighting unless of high candle-power, for most of the advantages which pertain to them when used in a house, disappear when they are taken into the street. The public look for a brilliant light and get only the equivalent of a good gas jet, and have to pay dearly for the luxury. They are exceedingly adaptable to the lighting of railway carriages. They know no equal for ship-lighting, their usual competitors in such cases being bad oil and worse lamps. In the case of passenger steamers expense is not of paramount importance; hence it is not to be wondered at that in this work incandescent electric lighting now reigns supreme. Incandescent lamps should prove of inestimable service in mines and in the bunkers of ships, where the chief difficulties to be contended with are want of portability and the risk of sparking between the broken ends of a wire or at switch contacts. These are trifling matters which must soon be conquered, and there is but little doubt, that before long the Davy and Geordie 'safety' lamps will be relegated to historical museums. There is a scope for incandescent lamps for the use of divers, and in many surgical examinations and operations, as well as for the microscope and the optical lantern.

In order to estimate the amount of light emitted by any luminous source, electric or otherwise, a large number of 'photometers' or light-measurers have been devised, but excellent as some of these may be in theory, they have, when applied practically, two serious defects. Measurement of every kind requires some unit or standard with which to compare the substance or force it is desired to measure; and it is pre-eminently essential that this unit or standard shall be fixed and invariable, and that it shall, without very much trouble, be reproducible. The majority of units comply more or less with these requirements; the one unit which does not, which is never fixed, but is always liable to variation, is the so-called unit of light. With us in England, the official unit is the 'candle-power,' which is assumed to be the light produced by a 'standard candle' weighing six to the pound and made to burn 120 grains of spermaceti wax per hour. The length of the candle varies slightly with different makers, ranging from 8¼ to 9 inches measured from the shoulder, where the diameter is about 0·8 in., the diameter at the bottom increasing to 0·85 or 0·9 in.

In practical work a straight candle is selected and cut into two equal parts, which are subsequently used together on a short bar placed at right angles with the scale-bar of the photometer. The two flames give a more reliable, or better average result than a single one. Candles are lighted ten minutes before the commencement of testing so as to allow them to arrive at their normal rate of burning, which is shown when the wicks are slightly bent over and the tips glowing. In fixing them in position, the plane of curvature of one wick should be at right angles to the plane of curvature of the other. If the candles are used when the wicks are straight or when a little knob or rose of carbonised thread has formed at the tip, the tests will give erroneous results.

The special requirements of a standard flame are that the combustible must be of known and definite composition; the conditions of burning must be of a simple and definable character, and the nature of the combustible, as well as the conditions of burning, must be such that atmospheric changes may produce a minimum effect upon the light.

Now white spermaceti has a melting point of 109°, but a small quantity (varying from four to five per cent.) of beeswax with a melting point of 140° is usually added in order to prevent the crystallisation of the spermaceti. The spermaceti itself is not a definite chemical substance, its constituents varying considerably, whence it fails to answer the first requirement, for the consequence of the differences in the proportions of the natural and added constituents is that small variations are found to occur in the melting point.

The number and size of the threads in the wick, its chemical treatment, the closeness of the plaiting of the strands, and the degree of tightness with which the wick is stretched, are also conditions which affect the light of a sperm candle, yet they are all left undefined by the Acts of Parliament; and, in practice, manufacturers differ in regard to them.

Even were the candles made as exactly alike as possible there are other conditions of variation which cannot be eliminated. For instance, the light varies from moment to moment as the wick bends over, as the knob at the end of the wick accumulates or burns away, and as the cup fills or empties itself of melted sperm.

A number of experiments made by a committee appointed by the Board of Trade showed that while the candles from a single packet gave fairly concordant results, the average obtained by ten experiments with one packet differed as much as 15 per cent. from the average obtained by ten experiments with another packet. In 115 determinations a maximum variation was found between two pairs of candles of 22·7 per cent. in illuminating power. All these experiments were made by one observer, working with one apparatus and in the most uniform manner possible.

The method of taking the average of three consecutive candle determinations does not therefore serve to eliminate the errors of the candle standard, for the candles employed may be taken from a packet containing candles of a uniformly high or a uniformly low illuminating power.

Standard candles are greatly affected by slight differences of treatment, so that a candle which gives a certain amount of light in the hands of one operator, may give a widely different result when used by a second operator.

The extreme sensitiveness of standard candles to differences in treatment is shown by the following typical experiment. Four official gas examiners tested on the same day a specially stored sample of coal gas. They used the same photometer, and candles from one packet selected for the uniformity of the candles contained in it. The mean of two closely agreeing testings by one examiner gave the illuminating power of the coal gas as 16·5 candles, while the mean of two closely agreeing testings by another gave the illuminating power of the coal gas as 19 candles.

Mr. J. W. Dibdin has reported very adversely upon the standard candle. He found on one day that the average of the tests with candles made by one firm (A) showed the illuminating power of a certain gas flame to be equal to 15·8 candles, while candles manufactured by another firm (B) gave a value of 14·9 candles ; on another day candles A gave a value of 14·8 to a constant gas flame ; while candles B gave a value of only 12·9.

It can therefore be readily conceived that a total variation of

10 per cent. is almost a normal result, while far greater differences are of common occurrence.

Another cause of unreliability under certain conditions, is, that when the temperature of the testing room rises above the normal the candles invariably give discordant results, sometimes indicating over 25 per cent. more than the known value of the comparison flame. The principal cause of variation is, however, the varying form and variable structure of the wick, which at one time had eighteen threads in each of its three strands, while at the present time the number has increased to twenty-one and twenty-three. Various improvements have been effected in the processes for 'drying' the spermaceti, or freeing it from oil, and the drier spermaceti now manufactured seems to require a wick containing more threads of cotton to raise it in the melted form and cause its combustion at the required rate of 120 grains per hour. But candles with thick wicks give less light than those whose wicks are thinner. Thus the effect of the improvement in the manufacture of spermaceti has been that standard candles give less light now than they gave ten years ago, and probably still less than they gave at an earlier date, when the average consumption of candles of six to the pound was 140 grains per hour.

A further very apparent objection is that the illuminating power is subject to fluctuations from minute to minute, owing to variations in the length and form of the wick, and to the filling and emptying of the cup of the candle, according to the movements of the surrounding air.

Sufficient has been said to make manifest the imperfections of the spermaceti candle as a standard.

One of the sources of error, viz., the irregular consumption of the spermaceti, can be to some extent allowed for by weighing the candle before and after the tests are made, the time of burning being also noted. If the consumption has not been at the exact rate of 120 grains per hour, the light emitted should be deemed proportionately different in intensity, and the measured intensity of the light as observed by the photometer, should be accordingly increased or diminished in the same proportion by a simple rule of three calculation. Thus if a lamp has been measured by the apparatus as giving a light of 17·6 candles, but the candles have been burning at an average rate of 116 instead of 120 grains, it follows that 120 : 116 :: 17·6 : x=17·01. A delicate balance is supplied with the better class of photometers, by means of which the rate of consumption can be readily ascertained.

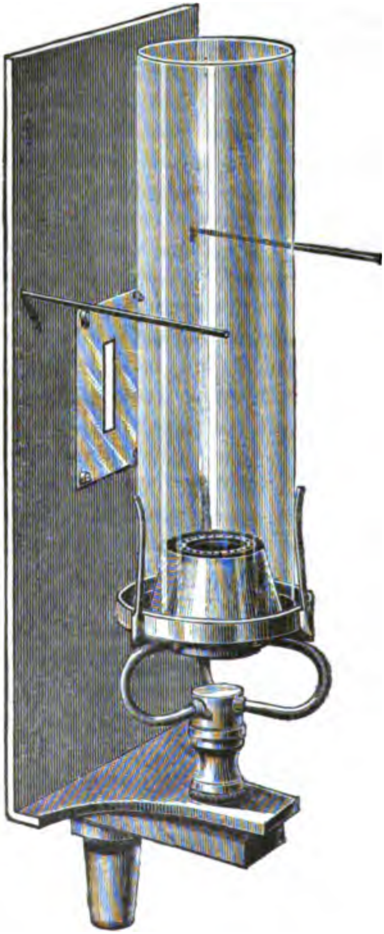
In Germany a standard paraffin candle is employed, but no better value can be attached to it than to the spermaceti candle.

The French sometimes use a stearine candle as a standard, but the actual French official standard is the 'Carcel' lamp, in which purified colza oil is consumed at the rate of 42 grammes per hour, and in which, of course, a wick is employed. The wick is cylindrical in shape and gives, therefore, an 'Argand' flame. It should be woven with 75 strands and weigh 3·6 grammes per decimetre of length. The chimney is 29 centimetres in height, its diameter being contracted at a short distance above the wick, from 47 to 34 millimetres. A good white light is produced, but from what has been said when discussing candles it will be evident, that for making exact tests, extreme care must be exercised in the manufacture and use of the lamp, and the combustibles. The chemical composition of the oil is liable to variation, and the simple fact that a wick is employed opens the way to a host of irregularities. It is, however, less affected by air-currents, &c., and is preferable to a candle. The standard Carcel is computed to be equal to about 9·5 standard spermaceti candles.

Several other attempts have been made to provide an efficient substitute for the standard candle, among others the lamp of Mr. Keates, in which sperm oil constitutes the fuel. This, however, involves the use of a wick, and the only suggested substitutes which may now be said to remain in the lists are the Methven screen and the Harcourt air-gas flame.

The 'screen' invented by Mr. John Methven is an exceedingly simple piece of apparatus. The instrument as now constructed by Messrs. Wright & Co. of Westminster is illustrated in fig. 282, and consists of an upright rectangular metallic plate or screen, having attached to its lower edge a horizontal flange or bracket, which supports a standard London Argand burner. This burner is supplied with gas through a plug or nosepiece projecting downwards below the flange. In the screen, above the level of the burner, there is a hole or slot which is covered by a thin silver plate, having a small vertical slot of such dimensions as to allow of the passage of just as much light as equals that afforded by two average standard sperm candles, when the gas consumed is sufficient to yield a flame three inches in height. It will be seen from the figure that a glass chimney is employed; it measures 6 inches high by 2 inches in diameter, the supply of gas necessary to produce the required flame being controlled by a tap, or in the better class of instrument by a micrometer cock capable of very fine adjustment. The two horizontal wires attached to the back of the screen, one on either side of the chimney, are placed at the requisite distance above the burner, and serve the purpose of determining when the prescribed flame length has been obtained. The apparatus is sometimes used with the richer pentane vapour as the illuminant (reference to which will be made presently). In such cases a second slide plate and slot is provided, of reduced dimensions, and furnished with a pair of horizontal wires 2½ inches above the burner, to which height the flame must be adjusted.

FIG. 282.



The Methven screen has the advantage that it forms a reliable and practical standard, easy to manipulate and not likely to ge out of order. Its simplicity of construction as well as of manipulation is self-evident, and its suitability for the required object has been demonstrated by Mr. F. W. Hartley, who made a number of lengthy series of tests with the apparatus, using slots of various dimensions. In one set of tests he found that with a 5 cubic feet per hour flame, of common coal gas of 14·02 candle-power, the difference in the photometric readings between a 3-inch Argand flame from the same gas and from cannel gas of 35·37 candle power, was only 0·7 per cent. These experiments tend to show that it is rather the height of the flame than the quality of the gas consumed which determines the luminosity, and this is a most important point, for it renders the standard virtually independent of any ordinary variations in the composition and lighting properties of the gas. A series of experiments was next made with standard candles which were employed to measure the light emitted by the common gas; the readings ranged from 13·24 to 14·588 candle-power, showing a difference of 1·348 candles, or 10·11 per cent. As these tests were made with gas supplied from the same holder, the result simply re-proves the utter unreliability of the standard candle. On the other hand, when the Methven screen was employed, the two kinds of gas being consumed in turn, the extreme difference was 0·83 per cent., and the mean difference 0·3 per cent. only.

While it is of course necessary that the height of the flame should be carefully adjusted, it is an important feature that the readings are not perceptibly affected by a variation of about one-tenth of an inch on either side of the prescribed height. The top of the flame should be as regular as possible, the burner of the best manufacture, and the chimney and screen scrupulously clean. As, however, it rarely happens that the top of the flame is absolutely regular, it is usual to so adjust the height that the extreme points extend about one-eighth of an inch above the horizontal wires. There is one other precaution, and that is, that the instrument should be allowed to get 'hot,' so as to arrive at the normal condition, before any reading is taken on the photometer. If this is neglected, erroneous results are almost inevitable, as the proportion of energy absorbed in heating the apparatus will be a varying quantity.

However, this only entails a delay of about five minutes after the gas is lighted.

It is scarcely to be wondered at that a standard so nearly approaching perfect uniformity in its indications, and so simple in construction and manipulation, should have found considerable favour in the electrical industries, where it is almost exclusively employed. To put the matter in a few words, it is a practical piece of apparatus. As Parliament has not yet prescribed any particular luminosity for electric lamps, manufacturers of electrical apparatus, and those supplying electricity, are not, like gas companies, tied down to the sperm candle. Mr. Dibdin says that 'the adjustment of the height of the Methven flame is a matter of too little certainty, and lends itself to variations of readings in the hands of a biassed or careless operator.' Granting, however, that there may be some slight trouble in properly adjusting the flame, it is not a matter of great difficulty, and the Methven standard is hardly likely to suffer more than any other from careless manipulation. Mr. Dibdin, however, says when dealing with the pentane standard that 'the adjustment of the height of the flame is a matter of certainty.' He also urges that the employment of a chimney (by Mr. Methven) is a serious disadvantage, as the portion of glass exposed to the slot acts as a lens, and therefore affects the results. The objection is, however, hardly fair here, for the width of the strip of glass involved is so very small (¼ in.) that it presents practically a plane surface.

In the standard suggested by Mr. A. Vernon Harcourt, and known as the air-gas or pentane standard, the combustible employed consists of a mixture of air with that portion of American petroleum which, after repeated rectifications, distils at a temperature not exceeding 50° C. This liquid consists almost entirely of pentane, its specific gravity at 15° C. ranging from 0·628 and 0·631.

To prepare the gas, Mr. Harcourt draws into the gasholder the required volume of air, chosen according to the capacity of the holder, and corrected for pressure, temperature, and tension of aqueous vapour ; then the corresponding proportion of pentane is poured into the gasholder from a measuring-flask or pipette. The proportion maintained between the air and the pentane, one cubic foot of air to three cubic inches of pentane, measuring the liquid at or near 60° Fahr.; or, measuring both as gases, 20 volumes of air to 7 of pentane.

When the pentane is poured upon the water in the gasholder with about thrice its vapour-volume of air above, it volatilises rapidly and completely. A few minutes are sufficient for the volatilisation of the liquid, and a few hours suffice for perfect diffusion.

The opening in the burner has a diameter of a quarter of an inch, and is at the top of a cylindrical tube one inch in diameter and four inches long, the thickness of the disc forming the mouthpiece at the top of the tube being half an inch. With a burner of these dimensions the mixture of air and pentane gas yields as nearly as possible a flame 2½ inches in height, when the rate of consumption is 0·5 cubic foot per hour.

The adjustment of the pentane flame to give the unit light (equal to the mean of a long series of tests with standard candles), may be based upon the observations either of its height or of the rate of consumption, and may be effected either by adjusting the height of the flame till the tip of it touches, without passing, a horizontal platinum wire stretched over the burner at the desired height, or by adjusting the rate at which the pentane gas passes through a delicate meter. Experience of the two modes of adjustment has shown that it is both easier and more accurate to trust to the setting of the height of the flame, and to use the rate of consumption as a control only, without taking it into account in reckoning the illuminative value of the gas tested.

No material variation in the light given by the standard flame occurs when, the height of the flame having been adjusted accurately to 2½ inches, the observed rate of consumption does not exceed 0·52 or fall short of 0·48 cubic foot per hour. As a rule, the rate only varies within the narrower limits of 0·51 and 0·49.

A series of experiments performed to ascertain the effect of variations in the proportion of air and pentane, demonstrated that an error or variation of 7 per cent. in the ratio of air to pentane causes a variation of 5 per cent. in the rate at which pentane gas needs to be passed through the meter to maintain a 2½-inch flame, and a difference of only 2 per cent., or ·03 candle, in the illuminative value assigned to the gas tested by comparison with it. But an error of even half this amount is rarely obtained in the actual preparation of pentane gas.

It is remarkable that only in 37 out of 468 testings, does the result of one testing differ from the mean result of the set of which it forms a part, by as much as 0·2 candle.

Tests were made with a variable height of flame, and the averages of ten observations made at the rate of one a minute, showed that with

Height of flame in inches . .	$2\frac{15}{32}$	$2\frac{1}{2}$	$2\frac{17}{32}$
The corresponding illuminating power was	99·25	100	100·75

Other experiments demonstrated that the illuminating power of the air-gas is but little affected by variations in the temperature of the room.

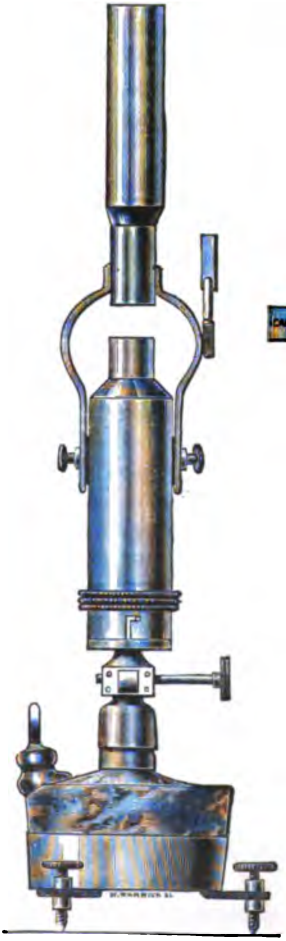
Mr. Dibdin is favourably impressed with the pentane standard, and in a report to the Board of Works, he recommended its early adoption.

Similarly the British Association Committee considered it to be reliable and convenient, fulfilling the conditions required in a standard of light, and they likewise urge the rejection of the Parliamentary candle as a standard of light, and the adoption of the pentane standard.

Mr. Harcourt has designed two or three portable pentane lamps, the latest and most convenient being that shown in fig. 283. In this case a wick is used, fitting loosely and moving freely within a tube which conducts heat downwards from the flame above, so as to give rise by evaporation to a quantity of pentane vapour sufficient to feed the flame, without the top of the wick being ever exposed to a temperature as high as that of boiling water.

The lamp (fig. 283) consists of a glass reservoir, with tubulure and stopper, of the form and size of a spirit lamp, mounted on a metal stand which rests on three levelling screws. The wick can be turned up and down in the usual manner by means of a double-toothed wheel, the spindle of which fits air-tight into the tube which supports it. The lower end of the wick (which is round and rather less than $\frac{1}{4}$ inch diameter) lies in the reservoir; the upper end is in a brass tube, about five inches in length, in which it can move up and down freely. The upper part of the tube is surrounded by a wider tube, about four inches in length and one inch in diameter; and the two tubes being joined together above and below by flat plates constitute the burner of the lamp. Around the burner is another cylinder open at both ends, of about two inches diameter, surmounted at the level of the top of the burner by a conical piece, terminating in a short tube whose diameter and length are about $\frac{3}{4}$ of an inch. Over this outer casing is a similar piece inverted, with the smaller tube below and the larger above. This second piece is connected with the first, the two being attached by two semicircular bands, so that the ends of the smaller tubes may be set at different distances apart, according to the amount of light which it is desired to obtain from the lamp. Through opposite sides of the upper tube, and above the ends of the connecting bands, are cut two narrow slots about $\frac{1}{8}$ of an inch in width, and $\frac{1}{2}$ an inch in height. These are placed at such a height that whenever the tip of the flame is visible between them the light emitted is definite and constant. The adjustment of the light, which may be set at either half a candle, one candle, or a candle and a half, is effected by means of cylindrical brass blocks whose length has

FIG. 283.



been very carefully adjusted once for all. One of these blocks is placed upon the lower tube, and the upper tube is lowered until it presses gently against the block; the screws which fix the connecting bands are then tightened, and the block is withdrawn. Since the blocks are made of the same diameter as the tubes between which they are placed, they serve for setting these tubes truly on the same axis, as well as at the right interval apart.

The point, or rather the horizontal ring, from the nearest point of which measurements are to be made when the flame of the lamp is used as a photometric standard, is midway between the tubes which surround the flame, and at a distance of half the radius of these tubes from their axis, which is also the axis of the flame. This position is defined to the eye by giving to the curved connecting bands half the width of the tubes. The zero of the photometric scale lies in the plane which passes through the edges, on either side, of the connecting bands. To mark this plane by a solid surface, a rectangular strip of brass is provided, which can be fitted on one side into the centre of the edges of the connecting bands. A small plumb-line is also provided, by means of which the lamp can be set truly vertical, and a small mirror by means of which the photometrist can observe without changing his position whether the top of the flame is between the slots in the side of the chimney. The tests to which the lamp has been subjected demonstrate that it is fractionally less efficient than the pentane standard.

The 'battle of the standards,' as already mentioned, is confined to the types invented by Mr. Methven and Mr. Harcourt respectively. It is possible that the latter is slightly more accurate than the other, but it is less convenient, and is for that reason very rarely adopted in practice, while the Methven screen is very extensively used by gas as well as electrical engineers. The Methven screen is always ready, and measurements can be taken within a very few minutes of lighting the gas. On the other hand, the amount of heat evolved by the pentane flame is so small that a considerable time elapses before the burner has assumed its maximum temperature, or attained the normal rate of burning. Careful manipulation and experience are necessary in the process of manufacturing the pentane, an operation which of course takes time to perform, and which would therefore frequently preclude its use.

Under the circumstances it is perhaps as well that our laws change but slowly, and that the legal substitute for the universally condemned sperm candle has not yet been determined.

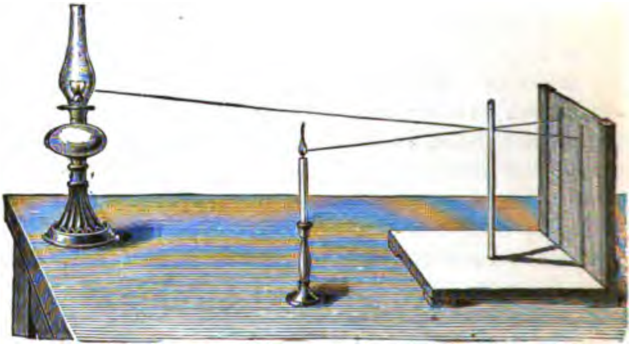
Supposing an absolutely reliable and permanent unit of luminosity to be available, we are still confronted by the second difficulty, viz., the want of a means of accurate measurement. Practical photometers are one and all simple comparison instruments, the light emitted by the standard and the source under test being compared simultaneously, and these comparisons must perforce be made by the eye. Unfortunately that organ is an untrustworthy piece of scientific apparatus and incapable of accurate discrimination. Its sensitiveness also varies considerably with the individual, so that the whole of any series of tests should be taken by the same experimenter, although even then there is some risk of personal error. Of course this difficulty is in some measure overcome by continued practice and attention.

All practical photometers are based upon the fundamental law that the intensity of illumination on a given surface varies inversely as the square of its distance from the source of light; and upon the fact that the distances of two independent sources of light can be so adjusted that their illumination of the given surface is equal. Then by measuring these distances the relative illuminating powers can be calculated.

The fundamental principle of the Rumford or 'shadow' photometer can perhaps be best illustrated by means of simple familiar apparatus such as that in fig. 284.

It consists of an upright ground-glass screen having fixed in front of it a small vertical rod. The standard light—in this case a candle—is placed at such a distance as to project a shadow of the rod upon the screen. The lamp, or other source, to be tested, is then brought into position so as to throw a second shadow close to that from the candle, and the exact position of the lamp so adjusted that the intensities of the shadows are as nearly alike as the observer can tell. The distances of the candle and the lamp from the ground-glass screen are then carefully measured and the comparative luminosities deduced from the law of inverse squares. For example, suppose the distance of the candle to be 12 inches, and that of the lamp $3\frac{1}{2}$ feet when the shadows are equal, then the luminosity is $1^2 : 3\frac{1}{2}^2$, that is to say, the light emitted by the lamp is $12\frac{1}{4}$ times as strong as that from the candle, and it may be called a $12\frac{1}{4}$ candle-power lamp. The comparative sensitiveness of the observer can be roughly estimated by moving the lamp to and fro for some distance, when, unless he is a professional photometrist, he will probably find that it is a very easy matter for the personal error to exceed 10 per cent.

FIG. 284.

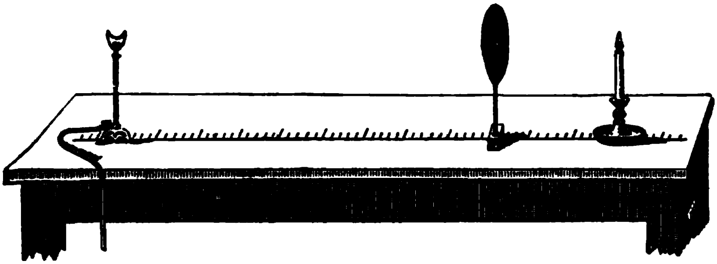


The principle underlying this instrument is simple, for it is evident that the shadow cast by the lamp is illuminated by the candle, while that cast by the candle is illuminated by the lamp, so that, if both shadows are reduced to the same degree of intensity, it can only be due to the effect of equal luminosities upon the surface of the screen derived from the two sources.

The Bunsen or, as it is often called, the grease-spot photometer is, especially for the beginner, an instrument by which more accurate results can be obtained; and it is the one most frequently employed. The principle of the apparatus is shown in fig. 285. A small screen of somewhat opaque paper is stretched on a metallic ring, which is mounted on a stand, movable along a graduated scale. In the earlier forms of this instrument, a semi-transparent grease spot was made in the centre of the disc by means of a little spermaceti dissolved in naphtha, but in the modern practical instrument, the whole of the paper, with the exception of a small central patch, is so saturated. To make an efficient screen is a matter of some difficulty, there being a particular thickness of spermaceti, which with each experimenter gives the best results.

The standard candle is fixed at one end of the scale, and the gas jet, or lamp (the luminosity of which is to be measured), at the other end of the scale, which should for convenience be divided into 100 or some multiple of 10 equal parts. The two luminants should be placed at such a height, that their centres are in a line with the centre of the screen, which can then be moved along the scale until the spot becomes invisible, and the whole of the surface appears to be uniformly lighted; or the screen and standard candle can be fixed, and the lamp under test moved along the scale to the required point.

FIG. 285.



The bottom of the stand carrying the screen (or lamp) should also be furnished with an index, and, the exact position of this index on the scale being noted, the relative distances of the two illuminants from the screen can be easily ascertained. Their luminosities can then be calculated by squaring these distances. The principle of this instrument is likewise simple. If a single light is held in front of the screen, the greased paper, which allows a portion of the light falling upon it to be transmitted through it, appears, when viewed from that side on which the light is placed, to be darker than the ungreased portion, which reflects liberally the rays falling upon it. If, on the other hand, the light is placed behind the screen, the grease spot or ring appears as a comparatively bright surface upon a dark ground, owing to the fact that the greased paper transmits a large portion of the light falling upon it, while the other part of the screen transmits scarcely any of the rays. When, therefore, the position of the screen between two sources of light is adjusted until the whole of the screen appears to be equally lighted, the two sides will be equally illuminated, the light transmitted by the greased paper being equal to that reflected from the ungreased paper. As a matter of fact, the grease spot is never capable of transmitting the whole of the light falling upon it, neither is the ungreased paper a perfect reflector nor absolutely opaque.

A beam of light falling upon a body is liable to be affected in three different ways; the rays may be transmitted, reflected, or absorbed. Bodies are called transparent when they transmit a large proportion of the rays, but all substances behave more or less as reflectors, for it is only by reflected light that non-luminous bodies become at all visible. All substances also, including even the best reflectors, absorb some of the rays, so that when a reflector is introduced into the measuring apparatus, some difficulty is experienced in estimating the amount of light. Professors Ayrton and Perry have invented a photometer, which, like their other productions, has a good scientific basis, and has been well considered in all its details. It was designed especially for electric lighting, and at a time when there was a great demand for means to measure the light from an arc lamp. It is based on the 'shadow' principle, but instead of moving the lamp away to a considerable distance in order to compare its light with that of the much feebler standard, a concave lens is employed, having the effect of scattering or dispersing the luminous rays, and projecting only a few of them upon the scale, whence it is known as a 'Dispersion' photometer. As the proportion thus utilised in casting the shadow can be readily determined, depending as it does upon the curvature and absorbing power of the glass, the direct result simply requires to be multiplied by a given constant to determine the relative luminosities. A plane mirror is employed to direct the rays upon the lens, the plane of the mirror being always adjusted to an angle of 45° with the incident beam so as to avoid the introduction of errors due to varying degrees of absorption for different angles of reflection. The mirror likewise carries a pointer moving over a graduated arc, by means of which the inclination of the incident beam to the horizontal can be indicated.

This instrument is no doubt very useful for laboratory purposes, but it is hardly one that could be placed in the hands of the average operator, for whom the necessary adjustments and calculations would be too intricate. This does not, however, detract from its value as a piece of scientific apparatus.

A beam of light has two other qualities besides that of illuminating a dark surface. It can easily be shown to possess more or less heat rays; also, that if certain compound substances are interposed in its path, chemical decomposition takes place. Were the three portions of the beam, viz., the thermal, the luminous, and the actinic or chemical rays, always united in the same proportions, we should have no difficulty in constructing a photometer accurate in its measurement and independent of the want of sensitiveness in the eye; for we could on the one hand use a thermometer, or a thermopile and a delicate galvanometer; or on the other hand a piece of sensitised paper such as is used in photography. But unfortunately the proportions vary considerably.

Tyndall has ascertained, as the result of a long series of carefully performed experiments, that the luminous rays from several sources of light bear but a small proportion to the obscure or non-luminous rays, the exact proportion of the former being from

An oil flame	3	per cent.
A gas flame	4	„
A white-hot spiral	4·6	„
An electric-arc light	10	„

The arc light appears here as the richest in luminous rays; it is also the richest in actinic rays, but the poorest in thermal rays. The various proportions differ, however, to some extent with different carbons, &c. The experiments demonstrate that, if either the thermal or the actinic rays are to be utilised for ascertaining the luminosities of electric lamps, they can only be compared together, or among themselves; they cannot be fairly compared with an oil or a gas flame.

In the practical measurement of electric lamps, modifications of the Bunsen photometer are, as we have indicated, generally employed. The form most frequently met with is the Letheby, which was designed for gas testing, and which therefore possesses many refinements unnecessary for electric light testing. The Bunsen disc is enclosed in a double conical tube or box to screen off extraneous rays of light, and small angular mirrors are placed opposite a pair of openings in the side of the tube, to facilitate observations of the two sides of the disc. The 'Universal' photometer, designed by the late Mr. Hartley, is simple, cheap, and efficient, and can be used for estimating the luminosities of arc or incandescent lamps, in a horizontal or in any other direction. It consists of a long narrow table, with two parallel grooves in the top; sliding in one of these are the Methven screen or other standard and the Bunsen disc, while in the other travels a scale, 21 inches in length, divided into tenths of an inch. For horizontal measurement, the lamp to be tested is fixed on an independent pillar at a known distance from the disc; if the lamp is suspended from the ceiling, an angle measurer is provided to facilitate the estimation of its actual distance.

It is the usual practice for an incandescent lamp to be carefully compared with some standard, such as the Methven screen. It is then in its turn employed as a standard of comparison for other similar lamps, requiring little attention, and affording a ready means of rapidly testing a large number of lamps. It is, however, only employed as a standard for a time, otherwise there would be some risk of error owing to a variation in the luminosity of the lamp. The method of testing arc lamps is somewhat similar. An incandescent lamp, after being standardised, is in this case, also, frequently employed as a standard, the arc lamp being placed on a scale at right angles with the photometer bar, which carries a mirror adjusted to an angle of 45° with the luminous beam, so as, in obedience to the law declaring that the angle of reflection is equal to the angle of incidence, to project the rays upon the greased disc, the quasi-standard being placed so as to illuminate the opposite side of the disc. The comparison is then made by adding the distance between the disc and the mirror to the distance between the mirror and the arc, and regarding this as the distance which has to be compared with that between the disc and the standard. A constant allowance has to be made for the absorption of the mirror, which for a certain angle varies with different samples of glass. It is obviously necessary that the arc should be so screened that none of the rays fall direct upon the disc, and that the angle of the mirror should be kept fixed. With a very powerful arc it would be possible to diminish the percentage of the rays falling upon the disc, by placing the lamp at a greater angle than that of 90° with the scale board or the axis of the disc. A fresh constant would then have to be employed, in accordance with the law that the intensity of illumination which is received obliquely is proportional to the cosine of the angle which the luminous rays make with the normal to the surface, allowance being also made for the increased loss due to absorption.

Where the space can be afforded, a photometer room should be provided, and fitted with opaque blinds, so that all extraneous rays can be excluded. The room, when candles or comparison flames are employed, should be free from draughts and vibrations.

CHAPTER XVII.

INSTALLATION EQUIPMENT, FITTINGS, ETC.

ONE of the most important details to be considered in connection with an electric light plant is the means to be adopted for transferring the energy from the generator to the lamp. In telegraphy it is a matter of secondary importance whether the line connecting the sending and the receiving stations measures 3,000 or 4,000 ohms in resistance, the number of primary cells employed for working the wire being simply varied according to this resistance. Consequently, unless a high-speed system of working is to be adopted, good iron wire answers every purpose, for it is a fairly good conductor, it is mechanically strong, and it is cheap. For high-speed working, copper is resorted to because the electromagnetic inertia of iron is too great to permit the necessary rapidity of current alternation.

In electric lighting, copper is always employed for the conductor. The current to be carried is usually very strong or heavy, and it is imperative that the loss of energy due to the resistance of the conductor should be brought down to the lowest practicable limit. Were iron to be employed, it would be necessary to give it six times the sectional area of the copper to obtain the same conductivity, and an iron wire or rod of such dimensions as it would be frequently necessary to employ would be too rigid for handling and bending. It would be necessary to make it in definite lengths and then to connect these lengths together at the place where they are to be used. But such a rod would also present very many additional difficulties in the way of insulation, and add considerably to the cost of that portion of the work. In fact, an insulated iron conductor would be considerably more expensive than one of copper offering the same resistance. The recently extended use of rapidly alternating currents is another reason against the employment of iron conductors.

It will be seen, from a study of the table given on p. 17, that the choice of materials for electrical conductors of any kind is really limited to the two metals above mentioned, viz., copper and iron; so that for electric lighting work we have no alternative but to use copper.

The table on the next page concerning the various sizes of copper wire generally employed gives some instructive details. It will be seen that most of these conductors are made up of a number of small wires stranded together, the chief objects being to impart greater flexibility and to reduce the risk of complete fracture.

Now as in overcoming the resistance of a conductor, electrical power is wasted, and as it costs money to develop electrical power, it is evident that in any commercial system such waste must be kept down to a minimum. This can be done by simply reducing the resistance, that is, by increasing the size of the conducting wires; but as this also is an expensive matter, care must be taken that the addition thus made to the expenditure in conductors is not so excessive as to more than counterbalance the cost of the power continually being saved. It has been laid down as a general rule, that, for the transmission of any given current, the size of the conductor most economical to employ is one offering such a resistance that the cost of the energy wasted per annum in heating the conductors, should be equal to the interest per annum on the original outlay upon them. Knowing the average current to be transmitted, it becomes easy to find the average electrical horse-power wasted in a conductor of any given resistance; but the cost of developing a horse-power depends upon many conditions, principally local, such as the cost of fuel, attendance, rental, repairs, prime cost and efficiency of the plant. And with regard to the conductors themselves, it must be remembered that it is not merely a question of the quantity and price of the copper employed, but also of the insulation and laying.

Most main conductors are, in England, placed underground, and as a rule the cost of laying considerably exceeds the actual cost of the wire.

Further, although the resistance of a wire one inch in diameter is only one-fourth of that of a wire half an inch in diameter, it does not cost anything like four times as much nor even twice as much to lay the thicker wire as it does to lay the thinner, for the

Number of wires in strand	Standard gauge of each wire	Diameter (in inches)		Equivalent to solid wire		Weight of Conductor per statute mile (lbs.)	Resistance at 60° Fahr. per mile (ohms)
		Of each single wire	Of the strand	Diameter (inches)	Area (square inches)		
1	22	·028	—	·028	·0006	12	72·52
1	21	·032	—	·032	·0008	16	55·53
1	20	·036	—	·036	·0010	21	43·87
1	19	·040	—	·040	·0012	26	35·53
1	18	·048	—	·048	·0018	37	24·68
1	17	·056	—	·056	·0024	50	18·13
1	16	·064	—	·064	·0032	65	13·88
1	15	·072	—	·072	·0040	83	10·97
1	14	·080	—	·080	·0050	102	8·884
1	13	·092	—	·092	·0066	135	6·718
1	12	·104	—	·104	·0085	173	5·257
1	11	·116	—	·116	·0105	215	4·225
1	10	·128	—	·128	·0128	262	3·470
1	9	·144	—	·144	·0162	332	2·742
1	8	·160	—	·160	·0201	409	2·221
3	25	·020	·042	·034	·0009	19	46·79
3	23	·024	·051	·042	·0014	28	32·50
3	22	·028	·059	·049	·0019	38	23·87
7	25	·020	·060	·053	·0022	45	20·01
7	23	·024	·072	·064	·0032	65	13·89
7	22	·028	·084	·075	·0044	89	10·20
7	21½	·030	·090	·080	·0050	102	8·893
7	20½	·033	·099	·088	·0061	124	7·342
7	20	·036	·108	·096	·0072	147	6·175
7	19	·040	·120	·107	·0089	182	5·002
7	18	·048	·144	·128	·0128	262	3·473
7	17	·056	·168	·149	·0174	356	2·552
7	16	·064	·192	·171	·0229	465	1·953
7	15	·072	·216	·192	·0289	589	1·543
7	14	·080	·240	·213	·0356	727	1·253
19	20	·036	·180	·159	·0198	402	2·261
19	19	·040	·200	·176	·0243	496	1·831
19	18	·048	·240	·211	·0349	715	1·271
19	17	·056	·280	·247	·0479	973	1·079
19	16	·064	·320	·282	·0624	1,270	·7154
19	15	·072	·360	·317	·0789	1,608	·5652
19	14	·080	·400	·352	·0973	1,985	·4579
19	13	·092	·460	·404	·1282	2,625	·3468
19	12	·104	·520	·458	·1647	3.354	·2709
37	16	·064	·448	·394	·1219	2,482	·3661
37	15	·072	·504	·443	·1541	3,142	·2892
37	14	·080	·560	·493	·1909	3,879	·2343
37	13	·092	·644	·566	·2516	5,130	·1772
37	12	·104	·728	·640	·3217	6,555	·1386
61	13	·092	·828	·728	·4162	8,477	·1072
61	12	·104	·936	·823	·5319	10,832	·0389

labour of removing and replacing the paving, earth, &c., would be almost the same in both cases. Again the insulation of the wire is an important and expensive item, which does not increase so rapidly as the resistance of a wire is reduced by an increase in its size; so that it does not by any means follow that a given reduction in resistance entails a proportionate increase in expense. It may be noticed incidentally, that when the diameter of a round conductor is doubled, although its sectional area and therefore its conductivity is increased four-fold, its surface is only doubled. Therefore if a current of four times the strength is passed through it, the heat developed will be four times as great (since power wasted $= C^2R$), while the surface at which radiation takes place has only been doubled. The temperature of the thicker wire will rise higher than that of the thinner one, when they carry currents in proportion to their conductivities.

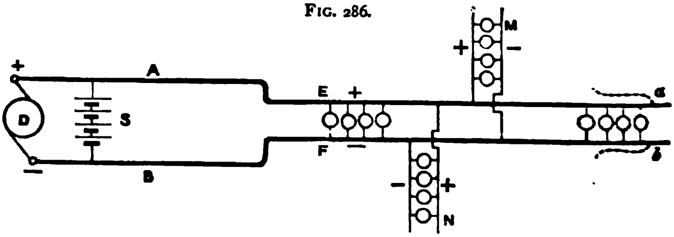
One advantage attending the use of bare conductors is the greater facility afforded by them for the radiation of heat as compared with covered conductors.

So many considerations, mostly special for every particular case, enter into the question of the best size and shape of the conductor consistent with strict economy, that we cannot discuss the matter fully here. But with regard to the reduction of resistance by the employment of high conductivity copper, it should be noticed that as the presence of a minute quantity of foreign matter causes such a great increase in the resistance of this metal, it is *always* economical to use the purest copper obtainable commercially.

In systems of distribution of electrical power by means of a constant current, the question is comparatively simple, as the current employed is not a heavy one, and has the same value at all times and in all parts of the circuit. The chief difficulty likely to arise is in providing for future extensions of the system when the potential difference which can be applied at the ends of the circuit is limited. The more interesting and more difficult problem consists in the supply of current to lamps, or other apparatus, at a constant potential; for then the main conductors have to carry a very heavy and variable current. The matter becomes more difficult if the lamps are distributed over a wide area, or are situated at a distance from the generating station. As has been pointed out in Chap. XIII., the power wasted may in such cases be reduced to a minimum, by transmitting it in the form of a small current at high pressure, and reducing the pressure at the required point, to a suitable value. But such a system has its disadvantages. Although the cost of the copper is vastly reduced, the high potential difference employed demands very efficient and expensive insulation, the engines and dynamos must always be kept running, and when very little power is being demanded the efficiency of the transformers and of the whole system falls to a low value. For even when the secondary circuit of a parallel transformer is disconnected, some current passes through the primary, and when only one or two lamps are joined up, the power appearing in the secondary may be but a comparatively small fraction of that absorbed by the primary. When the number of transformers is large, the total power wasted becomes considerable during the times when little or no light is required.

In the other method of distributing direct from the dynamo to a number of lamps all joined up in parallel, the chief problems to be faced are the heavy loss occurring in the mains and the difficulty of regulating the supply to each lamp.

FIG. 286.



Such an arrangement is indicated by the diagram in fig. 286, where D represents a dynamo capable of maintaining a constant potential difference at its terminals; A and B, the main leads from the machine to the nearest lamp; and E, F the continuation of those leads, between which the lamps are placed. Suppose there to be 100 lamps so joined in parallel, each requiring a current of half an ampere, and a potential difference at its extremities of 110 volts. The total current supplied by the dynamo with all the lamps in use would be 50 amperes, and this current would have to be carried by the main leads A and B. Supposing the resistance of A and B to be one-tenth of an ohm, the power wasted in overcoming this resistance would be 250 watts, and the consequent fall of potential 5 volts. Therefore the machine must develop at least 115 volts at its terminals in order to maintain 110 volts at the *nearest* lamp.

Now a further fall of potential would take place along the mains, E, F; suppose this to amount to 10 volts, then the pressure at the most distant lamp would only be 100 volts, while if this were raised to 110 by an increase at the dynamo, the nearest lamp would then be working at 120 volts. Even ignoring the waste of power, such a difference could not be permitted if similar lamps were used throughout the system, as some would be giving far above and others far below their normal candle-power.

It would, however, be practicable, but very inconvenient, to employ different types of lamp, placing those made to run at 110 volts at the end near the dynamo, and others constructed for 100 volts at the further end of the line, and so on. But even then, if the dynamo were perfectly regulating, the potential at the far end of the mains would rise considerably, when any number of the nearer or intermediate lamps were cut out of circuit.

Referring again to the figure, it will be observed that the mains at any one point only carry a current equal to that required by all the lamps beyond that point. Thus, while the portions, A, B, take the whole current, those portions between the last lamp and the last but one only carry half an ampere. The size of the mains might, therefore, be reduced by one hundredth as every lamp is passed, and the same density of current in the conductor be retained. This is equivalent to bunching 100 wires together to form the main, and taking out one of them at every lamp. If the 100 wires were separately insulated, that is to say, if a separate lead and return wire were used between the machine terminals and each lamp, the pressure at the ends of these leads would be constant; and since the resistance in each independent lamp circuit is also constant, the pressure at each lamp would be unaltered by any variation in the number thrown in circuit. This forms a means of maintaining a perfect regulation, although of course the actual pressure at the lamp would depend upon the resistance of its particular leads. Great as are the advantages of such a method, the expense would forbid its being employed in an installation extending over a large area. It will be seen, however, that with ordinary mains, if the resistance is sufficiently low to make the fall of potential very small, then the variation which would take place in the potential difference at the extreme end of the circuit becomes negligibly small. An extreme variation of 4 volts might be allowed, and then, by maintaining the normal pressure of 110 volts near the middle of the system, the nearest lamp would have but 112 volts and the furthest 108.

It is necessary to be able to observe in the engine-room the pressure existing at the far and near ends of the mains at any moment, so as to be able to keep one point as much below as the other is above the normal pressure; and this can be done by leading 'pilot-wires' from the mains at those points to a voltmeter placed at the generating station.

For instance, in fig. 286, a thin wire might be led from the point *a* and another from *b*, each to one terminal of the voltmeter, which would afford an indication of every variation at the extreme end of the mains. A second pair of pilot-wires might be led from the nearest lamp; or by leading one pair only, connected to the mains at the centre of the system, and keeping the potential there at 110 volts, a good average regulation might be maintained.

At an installation at Kensington Court, over two thousand 100-volt lamps are run in parallel, batteries of secondary cells being used in conjunction with the dynamos, for regulating, and assisting the machines to meet any large demand. Several circuits branch out from the engine-house, some of the lamps being 900 yards distant. At the extreme ends of all the mains, a pressure of 100 volts is maintained, while that at the nearest lamp does not exceed 102 volts. A pair of thin wires is led, as mentioned above, from the end of the mains, to a voltmeter in the engine-house, and when this instrument indicates a fall of potential (caused by the switching in of more lamps) the attendant immediately switches one or two secondary cells on to that pair of mains, in series with the existing cells, thus raising the pressure to the required value; the cells being of course cut out when the voltmeter indicates a rise of potential. The mains employed in this case consist partly of ordinary insulated cable, and partly of bare copper conductors stretched over porcelain insulators, in concreted channels.

Although on a simple parallel system of distribution, the arrangement is such that the whole of the lamps are connected in parallel between the two mains, it is evidently impracticable to join them directly across (as indicated in the case of the nearest and furthest lamps in fig. 286), when the mains are carried under the roadway. It is necessary to lead a wire from each main to every group of lamps, say to every house supplied, in the manner indicated at M, N. The higher potential mains are throughout marked +, and the lower potential, or return wires −. These subsidiary mains should be proportioned in size according to the number of lamps to be supplied by them.

It is not possible, however, to sufficiently reduce the resistance of a single pair of mains leading direct from the dynamo to maintain even approximately a constant pressure at all the lamps if they are distributed over a large area; a method of facilitating regulation in such a case, by the employment of subsidiary mains which feed the mains proper at certain points, but are not themselves tapped by lamp-circuits, will be described later on.

The method of employing a battery of secondary cells so as to assist in the regulation, or in the maintenance of a constant potential, is indicated in fig. 286, where S represents such a battery. The cells are joined in parallel with the dynamo, and are charged by it without any alteration in the connections being necessitated.

The interactions between the two generators—the dynamo and the battery—may be embraced under three heads. (*a*) When the E.M.F. of the battery is less than the potential difference at the dynamo terminals, the machine is supplying current to the lamps and at the same time charging the cells, the strength of the current passing through the cells depending upon the excess of the potential difference maintained by the machine over the E.M.F. of the cells. (*b*) When the E.M.F. of the cells becomes equal to the potential difference at the machine terminals both generators are equally active in feeding the lamp circuit. (*c*) When the E.M.F. of the cells rises above the normal—that is, above that potential difference which is required to be maintained at the terminals of the generators in order to maintain the right pressure at the lamps—then the battery not only feeds the lamp-circuit but raises the pressure at the machine terminals. This rarely happens, but the machine being shunt-wound, the effect is to increase the current through the field coils, giving a stronger field, which again tends to increase the E.M.F. developed. When the potential difference thus rises, it becomes necessary to cut out one or two cells to prevent the pressure rising sufficiently high to injure the lamps. A suitable switch is employed for this purpose, and the regulation effected by an attendant in accordance with the indications of the voltmeter.

It will be remembered that if the engine should break down, the cells would drive the shunt machine as a motor in the same direction; but an automatic cut-out should be provided to cut off the dynamo when the back-current from the cells exceeds a certain limit. A piece of apparatus capable of performing these operations was described in Chap. XIV.; it disconnects the machine when from any cause its potential difference falls below the E.M.F. of the cells. Under such circumstances the cells would be called upon, and should be able, to run even the whole of the lamps for a short period, or a portion of them for a considerable time.

It also becomes possible to economise power and the expense of attendance, by only running the machine during the hours when the demand is a maximum, allowing the cells to supply current to the few lamps required at other times.

It may occur to the student that a considerable saving in the mains would be effected by joining groups of lamps in series between the mains, all the groups being thus placed in parallel. This is so; for if the lamps were placed in sets of four in series, the potential difference between the mains would be four times that at the ends of one lamp, say 400 volts instead of 100. By this means the maximum current in the mains would be reduced to one-fourth, and the weight of copper correspondingly reduced, to give the same rate of loss of power.

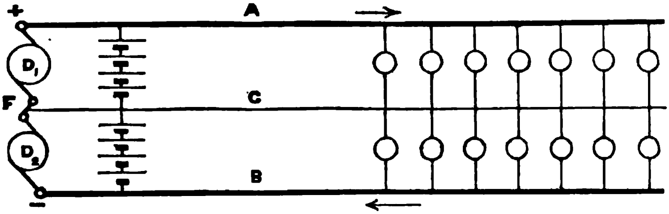
But some serious difficulties arise in connection with such a system; for instance, if the filament of one lamp in a set breaks, the other three lamps in that set are immediately extinguished: and if, to remedy this, the faulty lamp is merely short-circuited, the remaining three get too much current, and may also be damaged. Of course a device may be adopted to automatically switch in a second lamp, or to replace the broken one by a resistance equal to it; but the latter arrangement is undesirable on account of the waste of power; and in either case the extra fittings cause additional trouble and expense.

The same objection arises in the ordinary case of switching out one of a batch of lamps.

But even if the lamps are joined in sets of only two in series, a considerable saving is effected; and a method by which this can be done without introducing any of the difficulties referred to is indicated by the diagram in fig. 287. It is known as the 'three-wire system.'

Two equal dynamos, D_1, D_2, are joined in series, and connected to the mains, A, B, in the ordinary manner. That is to say, the positive terminal of D_1 is joined to the positive main, A, and the negative terminal of D_2 to the main, B, while the negative terminal of D_1 is coupled to the positive of D_2. Suppose each machine to be capable of maintaining a potential difference of 110 volts; then when they are so joined in series they maintain the mains A and B at a difference of 220 volts. The lamps being joined, two in series, across the mains as indicated, the potential difference at the extremities of one of them is 110 volts. A third wire, C, much smaller than the mains, connects the junctions of the pairs of lamps, and is also joined to the junction of the dynamos.

FIG. 287.



Now when the number of lamps between A and C is the same as the number between B and C, the potential is the same at every point along the wire, C. Hence there is no tendency for any current to flow along the centre wire; it might, in fact, be cut at any point, or removed altogether, without in any way affecting the working of the system. But when the lamps on either side of it are made unequal in number, this state of balance no longer exists. Suppose a lamp between A and C to be switched out of circuit; then the resistance between A and C is greater, and therefore the fall of potential becomes greater, than between B and C. But the mains A and B are kept at approximately the same potential difference, and if the difference between A and C is increased, it can only be by the lowering of the potential of C. The effect of cutting out a lamp between A and C, then, will be to lower the potential of C near the point where the lamp is disconnected. But the potential at the point F remains unaltered; consequently this difference of potential establishes a current along the wire C, from the junction of the machines to the lamps. The strength is equal to that which flows through one lamp circuit; it may, in fact, be considered as the current which passes through the additional lamp between B and C. If a lamp between B and C is now switched out, balance is again restored, and no current passes along C. When the number between A and C is made the greater, the difference between those leads is lessened, that is, the potential of C near the lamps is raised. This determines the flow of a current *from* the lamps to the junction of the machines along the centre wire. If the whole of one set of lamps were cut out, then the centre wire would have to carry the current supplied to all the lamps in the remaining set, in which case it would require to be as large as the other mains; in some cases the three mains are made equal, but it is usually possible to arrange the lamps so that this extreme case would never happen. Under favourable conditions the current which the centre wire has to carry, due to the difference in the number of lamps on either side of it, may be made comparatively small; and, consequently, the wire itself can be made much smaller than the mains proper.

It has been proposed to provide each lamp with a switch, by means of which it may be joined up between the centre wire and either main; the brighter light would be obtained from the main which already had the smaller number of lamps joined to it, and, consequently, the consumers, in their anxiety to obtain the best light, would assist in the regulation of the system.

Secondary cells may be employed in conjunction with the machines, as indicated in the diagram; two complete sets of cells are needed, their positive and negative terminals being connected to the mains and to the centre wire in the same manner as are the dynamo terminals.

A means of reducing the difficulty of maintaining a uniform potential difference along lengthy mains, is afforded by the use of independent conductors connecting various points in the circuit direct with the generating station, and these subsidiary leads are termed 'feeders.' In some cases the mains themselves are not connected direct with the generator, the whole of the current being supplied to them at suitable points by way of the feeders. When the potential difference at or near the particular point to which a pair of feeders is connected, varies (as it does, with a change in the number of lamps in use), this difference is compensated for by correspondingly varying the pressure applied to the feeders, or by some other means varying the current passing through them. When, for instance, the number of lamps in circuit is increased, the pressure between the mains falls, and more current is required to be supplied by the feeders, and *vice versâ*.

It becomes necessary, therefore, to provide some means for promptly indicating, at the generating station, the variations of the potential difference at the points where the feeders join the mains. This is readily supplied by the employment of pilot wires, after the manner already described, these wires being simply connected to a voltmeter. When the instrument shows a fall of potential, the electrical pressure along the pair of feeders is augmented until the distant point is raised to the required standard. On the other hand, should the potential difference in the mains rise, then that on the feeders must be reduced. But economical adjustment in this way is somewhat difficult of attainment. It would, for example, be hardly practicable to use a separate dynamo for each pair of feeders, and to continually vary its output to suit the demand. It is preferable to use one or more dynamos connected to a pair of 'omnibus' bars, from which the whole of the feeders radiate. The potential difference between these bars must be kept equal to the maximum required, and the regulation can then be effected by inserting resistance or counter electro-motive force in the respective feeder circuits.

The insertion of resistance coils, however, while it is effectual and convenient, is wasteful. A more economical plan is to introduce a few secondary cells in each feeder, in such a manner that they oppose the feeding current. The effect is simply to oppose a counter E.M.F. to the dynamo (since the cells have practically no resistance), but the potential difference is varied by the rather large steps of two volts at a time. In making any change both feeders must be similarly treated.

With the three-wire system it is obviously necessary to lead three feeding wires to each point and to connect pilot wires therefrom to two separate voltmeters.

The advantage of using several comparatively small machines joined in parallel, to supply the omnibus bars, is that a dynamo may be switched out and stopped when the demand for current falls.

When the feeders vary considerably in length, it may be advisable to divide them into two or even more groups according to their resistances, and supply the longer ones from a pair of bars maintained at a proportionately higher pressure than the similar bars supplying the shorter feeders.

Turning now to the methods of supporting, protecting, and insulating the conductors, we immediately observe that they naturally divide themselves into two classes, viz., overhead and underground.

The overhead system has the advantage of cheapness in construction, and it affords great facilities for inspection and repair, and for subsequent extensions. It is, therefore, generally employed where the local conditions are favourable, where the current employed is not so heavy as to require a very massive conductor, and where the potential difference is not excessively high. The system has, however, the disadvantage that the insulation is liable to considerable variation with weather changes. This can to a great extent be prevented by good construction, and the employment of properly designed 'insulators.' A series circuit, such as is used for arc or low resistance incandescent lamps, lends itself readily to the employment of overhead mains, since the current is in such cases constant and rarely exceeds ten amperes. A very small wire would be sufficient to carry such a current, but its size is really determined more by mechanical than electrical necessities.

For example, a wire of No. 12 B.W.G. would carry the current with safety, but a No. 8 or No. 10 is practically used on account of its greater strength. When the conductor is stranded, 7 No. 16's are employed, although 7 No. 20's would, from an electrical point of view, suffice. We ought perhaps to mention that all overhead bare conductors must be of hard-drawn copper in order to obtain the requisite mechanical strength. Ordinary pure copper is comparatively soft, and in a span of any considerable length cannot sustain its own weight; while in a gale, the wind pressure enormously increases the strain upon the wire.

Bare conductors are supported on insulators which are in turn supported by poles either of iron or wood according to local circumstances. One advantage pertaining to wood is that in the event of an insulator breaking, the conductor is still partially insulated from the earth, which would not be the case were an iron pole employed. Iron poles are obligatory for over-house work, or where appearance has to be taken into account. The best pole is that which consists of the complete trunk of a straight larch or other similar tree, which, after having been well seasoned, is thoroughly impregnated with good creosote. The natural life of the pole is enormously lengthened by this treatment. A convenient compromise is often effected by fixing a wooden top into an iron socket.

Insulators can be made from a variety of substances, but for climatic and other cogent reasons, white glazed porcelain is most frequently employed.

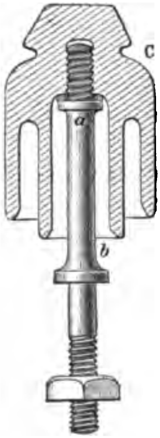
The chief requirements are hardness, smoothness, and imperviousness to moisture. Lacking either of these, the insulator is practically useless. It should be hard in order to resist abrasion by the wire; it should be smooth to prevent the accumulation of dust and dirt, to facilitate cleansing by rain, and to avoid the unnecessary wearing away of the conductor; and it should be impervious to moisture, in order that the rain should fall off instead of entering the pores of the substance and reduce, more or less permanently, its insulating properties.

Brown earthenware, made from clay, is, taking all things into consideration, also a good material. It is very hard, very durable, has a high resistance, and the glaze which it can take, although it is not so good and perfect as that on porcelain, is tolerably smooth and only allows the rain, unless the fall is very heavy, to gather in drops instead of forming a continuous film, as ebonite would do. Although porcelain offers a higher resistance than brown earthenware, the material varies very considerably, both in its constitution and in its manufacture. Some kinds are almost spongy, and as the glaze covers them there is no possible means of testing, except by breaking them. The glaze often cracks after a few months, and then, if the interior is at all porous, it absorbs moisture, and so in time loses its insulating properties. When perfect it is undoubtedly the best insulator available.

It must further be pointed out that the insulator should be sufficiently strong to bear the strain imposed upon it by the wire. When all is quiet the insulator has simply to bear the weight of half the span of wire on either side of it, but when there is much wind the strain is increased considerably by the swaying of the wire.

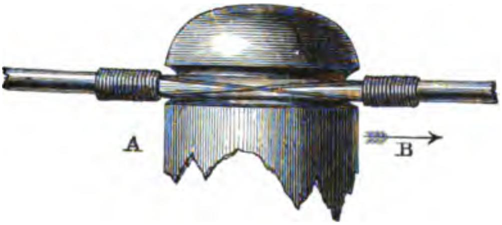
It is clear, then, that while the insulator must not be too large or heavy, it must be large and strong enough to sustain the weight it will be called upon to bear, and must have the maximum length, with the minimum area of surface between the wire and the iron pin or bolt supporting it.

FIG. 288.



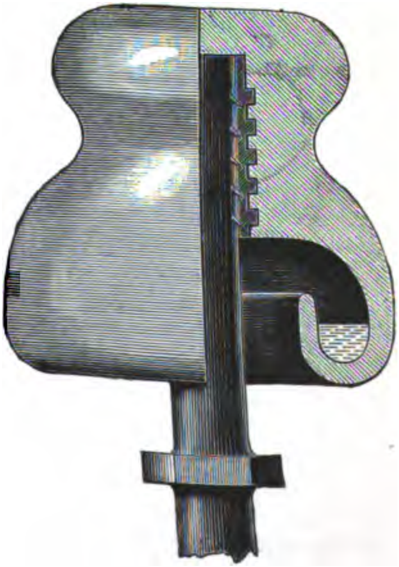
Considering the fact that the E.M.F. in an electric-lighting circuit is comparatively high, it is pre-eminently essential that the insulation should be of the best; parsimony in this respect is very likely to prove but the forerunner of disaster. When the line is straight, so that normally there is no lateral strain, and the conductor is not more than a quarter of an inch thick, the insulator illustrated in fig. 288 is suitable. It usually consists of a double 'cup' manufactured in one piece. The peculiarity about it is that it is provided with an open coarse screw thread by means of which it is screwed on to the bolt, permanently fixed to the arm or bracket on the pole. An india-rubber washer, placed at the bottom of the thread on the bolt, allows the insulator to be screwed on tight without involving a risk of splitting it. The principal advantage pertaining to the use of a screw bolt is that, in the event of fracture, the insulator itself can be replaced without necessitating the removal of the bolt. The method of fixing the wire to an insulator is illustrated in fig. 289. The conductor is laid in the groove, and a piece of thin binding wire, three or four feet long, is twisted several times round the conductor on one side, A, of the insulator; it is then wound round the insulator and is next twisted several times round the conductor on the other side, B, after which it is wound back again, round the insulator once more, and again over the conductor on the side A. Sometimes the bindings are soldered.

FIG. 289.



When high potential differences are employed, no trouble or expense should be spared to ensure the most thorough insulation possible. A form of insulator very largely employed for this purpose, especially in humid districts, where the risk of leakage is great, is illustrated in fig. 290. It is known as the 'fluid' insulator, from the fact that a quantity of oil is interposed in the path of leakage; the lip of the porcelain cup is bent up on the inner side to form a circular

FIG. 290.

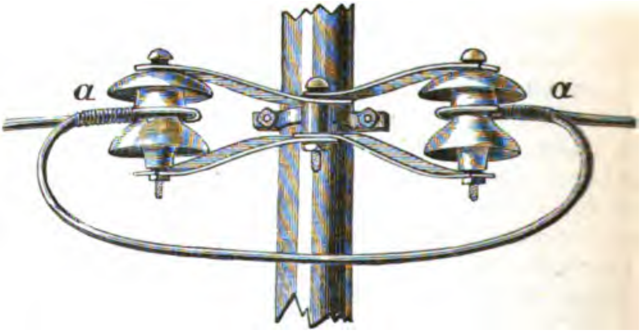


channel, in which the oil is placed by means of a small syphon capable of holding the required quantity. Experience has shown that very little dust accumulates in the channel, while the formation of a continuous film of moisture between the iron bolt and the conductor is entirely prevented.

These insulators are made in a great variety of shapes; in one case there is a separate oil cup supported on a pin which passes through the bolt. When necessary the pin can be removed, and the cup allowed to slide down the bolt, for the purpose of cleaning and refilling with oil; the cup can easily be placed in position again, and the syphon is therefore dispensed with.

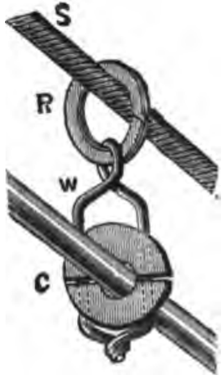
In fig. 291 is illustrated a form of insulator, known as the double shackle, which is useful on heavy lines. It consists of two insulators of porcelain of the shape shown; each has a stout iron bolt passing through it, and is supported by a pair of iron straps bolted to the pole, which, in the case illustrated, is of iron. The main wire is looped round the middle of each insulator, and fixed by a small binding wire wrapped on tightly. The straps of each insulator being independent of those supporting its neighbour, freedom of motion through a large angle is permitted, thus relieving the strain. The shackle should be employed in all cases where the wire makes an angle at the pole.

FIG. 291.



When an insulated aërial conductor is used, it cannot be attached to the insulators direct, because the friction which is always at work, would speedily cause the abrasion of the insulating material, and that at the very point where complete insulation is sought, viz., at the insulator itself. There is also the further difficulty that an ordinary covered cable has not sufficient tensile strength to enable it to support its own weight in a span of any considerable length. In such cases, a steel wire or rope S (fig. 292), is supported by shackle insulators, and carries a number of split steel rings, R. Engaging in each ring is a galvanized iron wire loop W, which supports a vulcanite chair C, and through which the cable is passed.

FIG. 292.

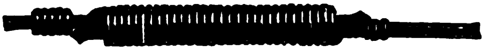


Sometimes the conductor is suspended midway between a pair of steel ropes by means of V-shaped pieces of iron wire, each piece being attached to three small reels of white porcelain threaded one on to the conductor and the others on the ropes.

One of the most important details in connection with the running of electrical conductors is that of jointing. The chief features which should pertain to a well-made joint are, that the electrical continuity should be fully maintained, that its mechanical strength should be at least equal to that of the conductor itself, that no free ends should be left on the finished joint, that it should be durable both electrically and mechanically, that it should be as compact as possible, and that with a covered wire the insulating coating should be made continuous and as uniform as possible.

For solid conductors up to a quarter of an inch or so in diameter, there is no better joint than that known as the ‘Britannia’ (fig. 293), which illustrates a joint of this kind made between two lengths of No. 8 B.W.G., bound with No. 16. The ends of the two conductors are carefully scraped and laid side by side for a distance of about two inches, about an inch or so at the extremity of each of them, having been previously bent up at

FIG. 293.



right angles to the axis of the wire. They are then wound over tightly, with several turns of thin binding wire. The binding is commenced on one of the wires only, round which four or five turns are wound; it is then continued as close as possible over the two wires, until the turned up portion of the second wire is reached, a few turns continued round the single wire completing the winding. The joint is finished by carefully and completely soldering it into one mass, and cutting off the then protruding ends of the wires, stray pieces of solder, &c. A joint made in this way approaches as nearly as possible to perfection, for its resistance is less than that of the other portions of the conductor, and its mechanical strength is much greater.

The method of jointing a covered stranded conductor is simple. Supposing it to be a 7-wire strand, the insulating covering is removed from each end for a distance of a few inches, care being taken to avoid nicking the copper. All the separate wires are then opened out and the centre wire on each of the ends to be joined, is cut off short. The two sets of wires are next brought end to end, and laced together, just as would happen when two hands are placed palm to palm, and the fingers of one hand placed between those of the other. This being done, the protruding ends of each conductor are wrapped closely round the other, the two wrappings being in opposite directions. The joint is then trimmed round with the pliers, and the whole well soldered together. The soldering is a more important matter than would at first sight appear, since the solder is relied upon to maintain the electrical continuity. Every care should therefore be taken that the copper surfaces are scraped clean before making the joint, that they are not handled more than is absolutely necessary, and that steps should be taken, as far as possible, to prevent oxidation. A very good plan is to use tinned wire, and to employ only resin as a flux. The conductor-joint having been completed, the insulating covering is then made good. If the material is gutta-percha, the conductor is wrapped with several layers of gutta-percha tissue which is softened by warming with a spirit lamp, and kneaded by the fingers to expel air bubbles. A few layers of gutta-percha strip are afterwards similarly applied, warmed and surfaced up with a warm metal tool, prepared tape being wound on to complete the joint. When the insulating material is india-rubber, strips of pure rubber are employed instead of gutta-percha.

When the conductors are to be laid underground, the chief difficulty to be contended with is the provision of efficient and durable insulation. The simplest method is to support the bare conductor by suitable insulators, after the manner described in Chapter XII. The distance between the insulators depends either upon the rigidity of the conductor, or upon the tension which it can withstand. Since every insulator is a point of leakage it is obviously necessary that their number should be reduced as far as possible.

In some electric lighting installations the bare conductors are supported by ordinary porcelain insulators fixed in a brickwork conduit with a concrete lining. In others, such as that in the Pall Mall district (London), in which the three-wire system is employed, the mains are carried in underground channels almost oblong in section, and made of cast-iron. At the junction of adjacent lengths a groove is formed in the sides of the channel, in which, at right angles to the length of the channel, is fitted a stout porcelain slab. The under edge of the slab is arched to allow the free flow of water along the bottom of the channel. The slab has also three deep vertical slots across the top, the centre one being somewhat narrower than the other two. Each conductor consists of a number of bare copper strips placed edgeways in the slots, and drawn tight enough to prevent contact laterally, while the depth of the strip is sufficient to prevent sagging. The centre conductor is formed of fewer strips than the outer mains; while the conductivity of all of them can readily be reduced beyond the points where branch circuits tap the mains, by reducing the number of strips. Long experience with underground chambers and channels, such as are employed for many other purposes, has shown that it is impossible to prevent the accumulation of water within them; hence the necessity for amply providing for the ready escape of water, that is to say, the conduit must be well drained. Electric light engineers have not yet had a sufficiently lengthy experience to enable them to appreciate fully the real difficulties which await them, such as those due to the corrosion of the iron and the falling of scale from the roof and sides of the channel; and to the incrustations and fungoid growths which manifest themselves in damp underground chambers. It would appear to be essential that good drainage should be supplemented by ample ventilation. Even were a conduit to be made water-tight there would still be sufficient moisture caused by condensation to oxidise the iron and make the surfaces of the insulators damp; although the passage of a heavy leakage current tends to dry the surface over which it passes.

It will, however, be evident that were the pipe containing the conductors filled with some good liquid insulating material, this accumulation of moisture with the attending disadvantages would be avoided. Paraffin oil is a liquid which has remarkably high insulating properties, and is, therefore, available for this purpose, but with a conduit constructed in the ordinary way, the quantity of oil required would be enormous. On account, however, of its high specific resistance, a thin film suffices to prevent leakage from one conductor to another, even though the potential difference between them be very great. The Brooks system is based upon this principle. So far the only application of it in this country has been to telegraphy, where, however, it has proved to be both reliable and economical under almost the worst possible conditions. A cable was made of forty cotton-covered copper wires of about No. 18 B.W.G. These were bound round with ordinary braid and drawn into a wrought-iron pipe of about $1\frac{1}{4}$ inch internal diameter, the length of the cable being about $1\frac{1}{2}$ mile. The ends of the pipe by which the cable enters and leaves were sealed for a distance of two or three yards with paraffin wax, and paraffin oil was then supplied from a reservoir placed at one end at such a height as to be above the level of the other end. The joints in the pipe were made as secure as possible, but for some time the line was subject to a series of faults, caused by the leakage of the oil. The average loss may be put down at about thirty gallons a month, although from February to September 1889 only thirty six gallons had to be added. It is essential that the pipe should be not only water-tight, but also paraffin-tight. The paraffin has, in fact, been known to exude through the iron itself, and stand in small beads on the outer surface; hence the necessity for using the best wrought-iron pipes. The chief objection to the system, the insulation-resistance of which is almost infinite, is that it affords few or no facilities for branching or T-ing.

The insulation-resistance being practically infinite, the system merits the serious attention of electric light and power-transmission engineers; but in cases where the mains are tapped at frequent intervals, the difficulty of making the branch connections will probably prove a serious drawback. In telegraph work, when two or more of the conductors get into contact, through the leakage of the oil, the fault is removed by refilling the reservoir, and so forcing more oil into the pipe; but a serious accident might arise from such a fault were the conductors to be employed for the transmission of heavy currents or currents of high potential difference. Some substance other than paraffin wax would also be required for sealing purposes, for were the conductors to become heated through a short-circuit, the wax would be melted and the oil allowed to escape.

Another method of insulating underground conductors, and the one generally adopted, is to cover the copper with some durable substance of high specific resistance, such as india-rubber or gutta-percha.

In all such cases it is essential not only to efficiently insulate the conductor, but also to protect the insulating covering from deterioration by exposure, and to protect the whole cable from mechanical injury. When these points are very carefully attended to, an installation with insulated underground cables for the mains is very reliable, and gives little or no trouble in maintenance. But carelessness in manufacture or laying, or the use of inferior materials, gives rise to troublesome and most expensive repairs.

At present there is a tendency towards false economy in this matter. A thin covering of the insulating material is placed over the conductor, and when new and absolutely perfect the insulation may test higher than is actually essential in practice. But the slightest indentation or abrasion of the covering, such as may easily happen, and does happen, in handling during the process of laying, even if it does not quite expose the copper, leaves such a weak spot that the development of a 'fault' there, becomes only a question of time. The insulating covering, of whatever material, should be of reasonable thickness, not so much for the purpose of obtaining an extremely high initial insulation-resistance, as to ensure its maintenance at a fairly good value. Gutta-percha must be used with caution. If not exposed to light and air it is practically imperishable, and it may therefore be used with advantage under conditions which are at all similar to those obtaining in the case of a submarine telegraph cable; but it quickly cracks and perishes if employed in a dry, airy situation. In such cases india-rubber would be preferable; but for underground work pure and simple there is very little to choose between these two substances. With rubber, the copper requires to be tinned in order to protect it against the sulphur which rubber insulation usually contains. Gutta-percha, however, softens at a lower temperature than does india-rubber, and hence is more likely to allow the conductor to become decentralised when heated by the current.

These materials are the best available for insulating purposes, but they are expensive, and a large number of substitutes have been introduced. Some of them are fibrous in their constitution, and are impregnated with an insulating oil. Their specific resistances are lower than those of percha or rubber, but this is not a serious drawback provided the coating is sufficiently thick. They are not as a rule impervious to moisture, and require therefore a waterproof covering.

In some instances the temperature at which the compound softens is very high, whence the tendency to decentralisation is reduced.

Bitumen is a good insulating material, but it softens at a low temperature, and even at normal temperatures it is so plastic that the weight of the conductor itself would cause it to sink through the coating. The processes employed by the Callender Bitumen Co. overcome these objections. The material is vulcanised or treated with sulphur, with the result that, while retaining its high insulating properties, it becomes rigid and holds the wire permanently in position, even though the temperature of the conductor be considerably raised. The conductor is usually of stranded copper wire, tinned to protect it from the sulphur. It is first coated with a sheath of the vulcanised bitumen, applied under heavy pressure in one solid layer to the required thickness. This sheathing is then covered with cotton tape treated with bitumen, the number of layers ranging from one to five ; the cable is passed through a bath of hot compound after each serving of tape. The next process, for underground cables, is to apply a coating of jute yarn, and after another passage through the bath to cover it with hemp braid. Most of the cables are subjected to this treatment, the higher degrees of insulation being obtained by increasing the thickness of the dielectric—that is, of the vulcanised bitumen. For the smaller cables, such as are employed for indoor work, a layer of parchment tape is interposed between the conductor and the bitumen.

For important underground work the company has three distinct systems, the cables in all such cases being made as already described with the higher degree of insulation. In the first of these systems, a rectangular cast-iron trough is laid in a trench. The troughing is made in six-foot lengths, the thickness of the metal ranging from three- to five-sixteenths of an inch ; the internal dimensions vary according to the number and size of the cables, but in all cases the cable is kept at some considerable distance from the iron. One end of each length of the troughing fits into a socket made at the adjacent end of its neighbour. The two lengths are then bolted together and the joint sealed with bitumen. The cables are supported by a number of wooden bridges, generally placed at intervals of two feet. Each bridge before being placed in position is treated with bitumen, and has two or more vertical slots, according to the number of cables, each slot being rounded at the bottom, and just wide enough to fit the cable. A small quantity of natural or unvulcanised bitumen is run along the trough, and the bridges are imbedded in it before it solidifies. The cables are then laid in position in their respective slots, the dimensions of the wood being sufficient to keep them well clear of each other and of the iron. The trough is next filled up with pure bitumen and covered in with a one-inch layer of concrete, or an iron lid. It may be urged as an objection to this system that, the cables having been once laid, cannot in the event of a fault occurring be withdrawn ; but, on the other hand, the system permits of such good work being put in that the chances of a breakdown can be made very remote.

The second of these systems is designed to allow the cables, which are similar to those used in the previous case, to be withdrawn separately. The channelling consists of blocks of bituminous concrete made in six-foot lengths and jointed by a saddle-piece of the same material. The blocks are provided with longitudinal circular holes or 'ways,' varying in size and number according to the requirements, but only one cable is placed in each way. In most cases there are either two, three, or four ways, the diameters most frequently employed being 1½, 2, or 2½ inches.

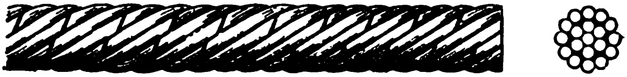
Draw-boxes are provided at convenient intervals, and the blocks having been fixed together in the trench, the cables are drawn in. This system has also the advantage that, should the cable-covering fail or give way, serious damage is prevented from the fact that the supporting material, *i.e.* the bituminous concrete, is a good insulator.

The 'saddle-pieces' embrace the sides and bottom of the blocks, and are provided with two grooves (one on either side of the joint), which are filled with bitumen.

In the third system the insulating material is fibrous in its constitution and is sheathed in lead. Over the conductor is wound a layer of parchment tape. Next to this is applied a rather thick layer of fine yarn, which has been dried at a very high temperature and then impregnated with boiling bitumen under pressure. The characteristic feature of this cable consists, in fact, in the processes adopted for the complete exclusion of moisture and air. Immediately after the impregnation is completed, and while the bitumen is still hot, the lead sheathing is put on direct with the aid of hydraulic pressure. The subsequent treatment varies with circumstances, but it is usually necessary to protect the lead from mechanical injury and the chemical effects of certain soils. For these purposes, the lead is passed through an asphalte bath and is then served with steel wire or ribbon, which is also covered with bitumenised tape or braid.

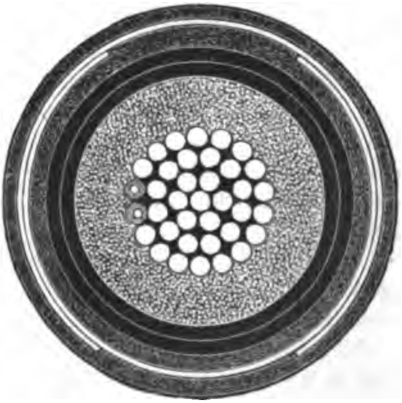
We have already described the method of making the splayed or long joint for stranded conductors, but in all Callender cables another form, known as the 'marriage' joint, is employed; a portion of the joint is illustrated in fig. 294. More skill and time are required to make this joint than are involved in the ordinary joint, but it has the advantage that the conductor is of uniform diameter throughout. It is also very strong and electrically good. Each strand is wound separately round the others and is cut to such a length that it abuts against the end of a strand from the other side of the joint. The end-to-end abutments occur at regular intervals, as can be gathered from the illustration; and the whole is well soldered. The covering is made good by pieces of materials identical with those already on the cables. In the case of the lead sheathing, an ordinary wiped joint might be employed, but owing to the uncertainty of always obtaining reliable plumbing work this method is not adopted. The cable ends are led through holes in the ends of a cast-iron joint-box, which after the ordinary insulating coating has been made good, is filled up with bitumen. A similar box, provided with three holes, is used at a T-joint.

FIG. 294.



A good type of electric lighting cable is manufactured by Messrs. Felten & Guilleaume, one form of which, designed for one of the mains on a three-wire circuit for incandescent lighting, is illustrated in fig. 295. The stranded core of high-conductivity copper is insulated with a layer of impregnated fibre, the thickness of which is about one-third the diameter of the conductor. Outside the fibre two coverings of lead are placed, as indicated by the black concentric circles in the figure. Over this is a layer of jute treated with an impervious

FIG. 295.



compound; and mechanical protection is afforded by a double sheathing of iron ribbon (shown white), the external covering being another serving of the impervious compound. This cable was constructed to be laid bare in a trench, and it contains the pilot wires which are necessary on an extensive parallel system. These two wires can be seen on the left of the conductor; they are of thin copper insulated with gutta-percha.

The lead sheathing is drawn on cold at an enormous pressure, and squeezes the fibre insulation into a solid mass. The two coatings of lead afford greater security against a small imperfection than could be obtained by a single coating with the same weight of metal.

When the cables are laid in an iron troughing, the iron sheathing is dispensed with, and the pilot wires are laid separately.

Wires inside a building must be efficiently protected to avoid damage or accident, as well as to maintain the insulation. A good plan is to run the wires along parallel grooves in a wood casing, as it is usually stipulated that the coverings of the two conductors should always be separated by an independent solid insulating substance. When it is necessary for one wire to cross another, a slip of wood is interposed. The casing can be made in a variety of forms, and if necessary can match the beading or cornice.

India-rubber covered with braided cotton forms about the best material for insulation for indoor work. Gutta-percha, for the reasons already enumerated, is less suitable, although its life can be considerably lengthened by protecting it from the atmosphere, which can be accomplished by carefully covering it with tarred tape.

We have already described certain pieces of measuring apparatus, but there are a number of other internal fittings which now claim attention.

The switch is a piece of apparatus which is in constant use, and for a variety of purposes, but chiefly to form a ready and expeditious means of making and breaking a circuit. The extension of the electric light has engendered a considerable development in the constructional details of such instruments, but in almost all cases the same general objects have been kept well in view. The forms of switch in use prior to 1878, from which time the revival of electric lighting may be said to date, are altogether inadequate for present purposes, mainly on account of the large currents which they are required to carry, and the high potential differences which may exist between the different portions of the apparatus.

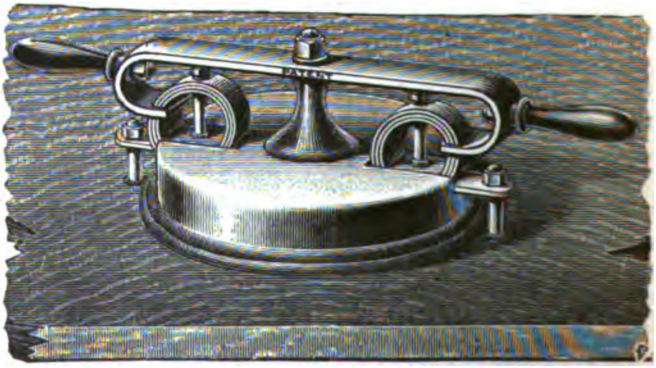
In order that a switch may be capable of efficiently performing its functions, its metallic parts must be sufficiently massive to carry the required current without heating or offering any appreciable resistance; the contact surfaces must for similar reasons be extensive ; the moving contact piece must press firmly on to the fixed one ; and simple striking contacts must give place to rubbing contacts, to avoid partial insulation through accumulation of dust and metallic oxide films. The circuit should not, when otherwise practicable, be completed through the axle upon which the rotating arm travels, unless a good independent rubbing contact between the axle and the bearing is provided, as dirt, oxide, &c., are liable to accumulate at the bearing surfaces, and in time impair the efficiency of the switch.

The switch should be so constructed that there is the minimum abrasion and wearing compatible with good and certain contact, and such parts as do wear away should be easily adjustable or cheaply renewable, so as to permit the re-establishment of good contact. In all cases, but more especially for currents of high E.M.F., the lever should be provided with a handle of insulating material. The terminals should never be so placed that in turning the handle there is any chance of the instrument being short-circuited by the operator's hand. When contact is broken the current (especially if the circuit contains any apparatus having considerable self-induction) sparks across the air space in the effort to continue its course, volatilising a portion of the metal surfaces. After such an 'arc' has been once established its maintenance is not a matter of great difficulty ; and it is evident that such an arc is quite competent to start a serious fire, besides in any case damaging the switch contacts. It is advisable to provide a snap-action, so that the lever is set decidedly either on or off the fixed contact, the spring being so arranged that the lever is jerked quite away when it is turned almost out of contact. The actual sparking can in a great measure be prevented by causing the contact to be broken gradually instead of suddenly. The movable contact can be made to quickly travel over a set of fixed contacts, throwing more resistance in circuit at each step, until the current has become so low that it is incompetent to cause a serious spark. Such a device need only be used in special cases. The contact surfaces can easily be protected by arranging two carbon rods, placed end to end, as a shunt, and allowing the contact between the two carbons to be broken just after that between the metallic surfaces. The sparking then occurs at the carbon surfaces, and the rods can easily be renewed when necessary. The base of the instrument should be of some good insulating material, not liable to warping or appreciable expansion or contraction. Wood should therefore be used with caution.

What is required is a material which is non-inflammable, a good insulator, does not readily condense moisture, or facilitate the accumulation of dust and dirt. Slate is a good material if free from impurities, such as mineral streaks or veins ; glazed porcelain condenses moisture freely, and is brittle, the latter objection also applying to serpentine.

With these introductory remarks we can describe a few of the various forms of switch now in use. The 'ring' contact switch (fig. 296) is undoubtedly one of the best for carrying heavy currents. It is mounted on a slate base, each terminal clip consisting of a number of split brass rings placed inside one another, the contact being made by forcing the connecting bar into the gap

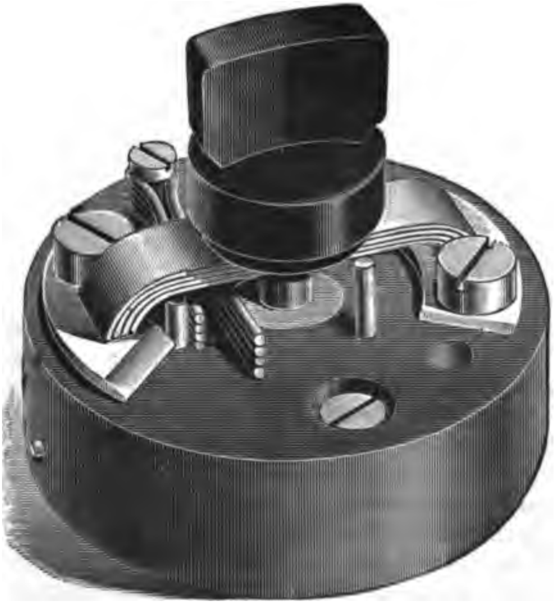
FIG. 296.



in the rings. This bar, which is a strip of stout brass with, in the particular form illustrated, the ends bent round, is provided with substantial wooden handles. As the contact surfaces wear away, the gap can be reduced by tightening up the bolt which it will be seen passes across the vertical diameter of the rings. Lugs cast on to the under side of the outer rings extend beyond the base, and are bolted to terminals underneath, or to tubular holders into which the main wires can be soldered. It will be seen that this form of switch practically answers every requirement, the safest possible connection being obtained, and the contact surfaces being self-cleaning. It is made to carry currents up to 1,000 amperes.

Messrs. Woodhouse & Rawson also make an excellent form of switch, shown in fig. 297. The switch bar consists of a number of—in this case four—bent strips of hard brass, which rub on to fixed blocks of a similar material. The edges of these blocks are

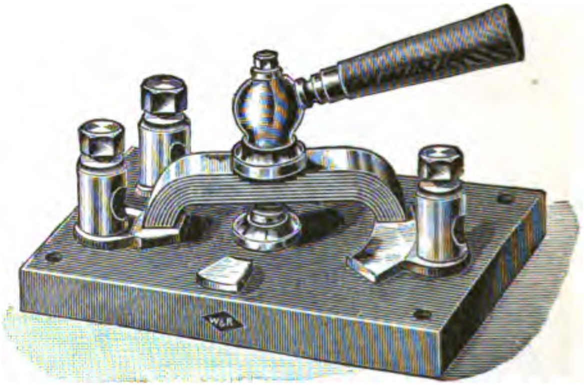
FIG. 297.



bevelled, to prevent the bar jarring against them, and at the same time to allow it to slide fully on to them, although the pressure is considerable. The switch has a quick break, almost instantaneous, owing to the action of a bent spring, which is compounded of four steel wires, as shown in the figure. This spring presses against a projection from the axle, which is edge-on when the switch is in the position shown, but which with a small movement is presented obliquely to the spring, allowing the latter to jerk the arm away, clear of the contact blocks. These switches are provided with metal covers which are fixed by a bayonet joint.

Fig. 298 shows a modification which is made to carry up to

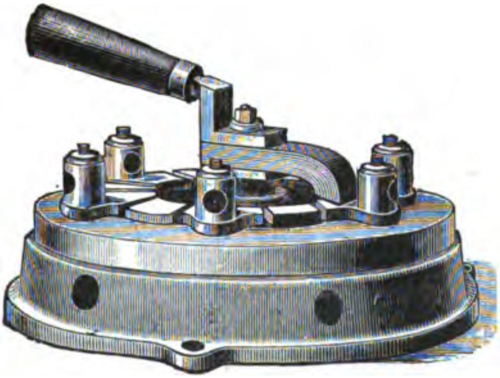
FIG. 298.



500 amperes. The contact arm or bar is made of several brass strips the extremities of which move over stout contact plates fixed to the slate base. This is a 'three-way' switch, the contact block, shown under the handle, being sufficiently large to allow the arm to complete the circuit from it to one or other of the two blocks near the opposite end of the arm. The circuit can also be completely disconnected, in which case the arm should be made to rest, in the intermediate position, on a pair of small plates, one of which can be seen in the front of the figure.

Fig. 299 illustrates a somewhat similar switch for enabling extra secondary cells to be placed in or out of circuit, one by one, during charge or discharge, as the arm is made to rotate. The short-circuiting of a cell is prevented by a coil of wire of suitable resistance mounted on a vulcanised fibre frame below the slate base, the whole switch being fixed on a hollow cast-iron frame, perforated in several places to allow a free current of air to pass through it.

FIG. 299.



Another very useful form of switch is that in which the movable arm consists wholly or in part of thin flexible copper strips, screwed firmly into square tubes or sockets, and rubbing edgeways over solid brass or copper blocks. In one such switch the arm consists of a stiff flat spring terminating in square holders, in which the flexible brushes, composed of a great number of strips, are held by set screws. This type has the advantage that there is always an extensive contact surface, that adjustment is easy, that the brushes are comparatively inexpensive, and that they can be readily removed for cleaning or renewal.

In another switch of this type the arm consists of a large bundle of long flexible copper strips, passed through a rectangular hole in the axle and fixed firmly in position by screws. In this case the brushes rub against the inner vertical faces of the fixed blocks, instead of over the upper horizontal surface.

A switch of some kind is required in connection with every incandescent lamp or group of lamps, and of this class there is a vast number in use, many of them being simple forms of those already described. Fig. 300 shows one made by Messrs. Fowler, Lancaster & Co., in which the wires are connected to a pair of brass blocks which in their turn are connected to two long flat springs, whose free ends ride over projections on the wood or ebonite bar A B. Each of these projections consists of two parts, one being a non-conductor and the other brass. In the diagram the flat springs rest on the two insulating studs, but on pushing A B inwards towards the left, the springs ride over and make contact with the brass studs, which being but the ends of a short brass rod passing through A B, complete the circuit of the lamp.

FIG. 300

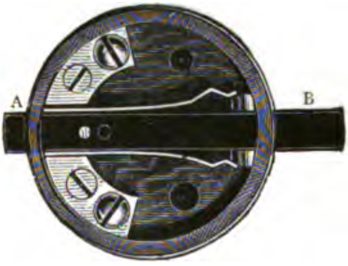


FIG. 301.

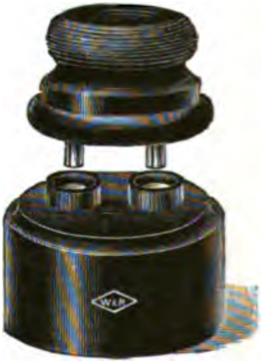


Fig. 301 illustrates a class of switch known as a wall socket, which is useful in cases where it is required to place a movable lamp in circuit at one or other of a number of positions, in such places as cellars, workshops, libraries, ship's bunkers, etc. The leads are joined to a pair of terminals in the lower block, which is permanently fixed in position. The upper or movable block carries the lamp, the terminals of which are connected to two split spring plugs, which can be pushed into the socket piece and so complete the circuit through the lamp.

Highly important as switches undoubtedly are in an electric light circuit, cut-outs can scarcely be said to be less so. The function of a cut-out is primarily to prevent damage being done to the apparatus, the leads, or the building in which they are placed, by means of an unduly strong current; and the way in which it affords this protection is by automatically disconnecting the circuit when the current from some cause, accidental or otherwise, exceeds a certain pre-determined limit.

There may be said to be two species of cut-outs, (*a*) those actuated by an electro-magnet, and (*b*) those consisting of a piece of wire or foil which melts or fuses with a current of definite strength.

A magnetic cut-out consists essentially of a coil of wire placed in the main circuit and provided with a movable core, or armature, to which is attached a strip of metal also forming a part of the main circuit. When the current rises above the prescribed strength, the coil attracts its core or armature with sufficient force to draw away the strip and break the main circuit. But it is necessary for the contact made by the strip with the ends of the main circuit to be very good and also frictionless, otherwise the pull required to break contact would be liable to vary. In the best instruments the two ends of the main circuit terminate in cups which are partly filled with mercury. A horse-shoe shaped copper rod is attached at its centre to the armature, and each leg dips into one of the mercury cups. The contact is thus reliable, but there is a chance of serious sparking occurring at the mercury surface when the contact is broken with a heavy current, especially if any large electro-magnet having considerable self-induction is included in the circuit. The advantages of such a cut-out are, that it can readily be adjusted to act with certainty with any given current, either by varying the tension of an antagonistic spring, or by altering the centre of gravity of the moving piece. It can also be arranged to automatically restore the connection when the current falls again to a safe value. Although this latter arrangement is not as a rule adopted, the apparatus can be immediately restored to its normal state by hand, when the cause of the rise in the current has been discovered and removed. It is manifest that the resistance of the apparatus must be kept extremely low to avoid serious loss of power. It requires a certain amount of attention and is expensive compared with the type next to be considered, viz. the simple fuse.

A fuse can be constructed so as to offer very little resistance, and therefore to absorb but little power. It must of course offer some resistance, since it is owing to the heat developed by the current in overcoming this resistance that the fuse is melted. Obviously a fuse made of a metal which has a low melting point requires comparatively little electrical energy to raise it to a state of fusion; and hence a fuse composed of such a metal may be made of lower resistance, and so absorb less power, than if a metal with a high melting point (such as platinum, 2,000° C.) were employed. In fact, with a well-designed fuse the chief cause of loss of power is likely to be in the careless connection of its extremities to the terminals of the main circuit.

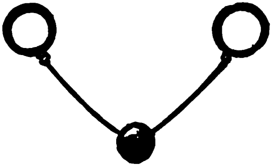
Such a cut-out has no working parts likely to get out of order or to need any attention, is very inexpensive, and, if properly designed, can be relied upon to act when the current reaches any particular strength, or at any rate within about 5 per cent. of it.

The fuse must be designed so as to break promptly and certainly, and manifestly it should not, if it can possibly be avoided, be allowed to get red-hot, otherwise the danger from fire becomes serious. The lower the temperature at which the metal employed melts, the less is the danger thus incurred. It must not be forgotten that good conductors of electricity are also good conductors of heat, and that therefore the terminal screws to which the fuse is attached conduct the heat rapidly away. This fact necessitates the fuse being made rather longer than would otherwise be the case; and while the terminals must be sufficiently massive to allow good and reliable connection, they should not be unnecessarily so.

It is almost superfluous to add that the metal employed should be durable, and not subject to change from any cause such as oxidation. Platinum fulfils this condition admirably, and yet it is a most unsuitable material for general work on account of the high temperature at which it melts. It is, in fact, easy to maintain it at a bright red heat for a considerable length of time. Tin, however, melts at 235° C.; it is very durable, only slightly oxidisable, and, taking all things into consideration, is undoubtedly the best metal for a fuse.

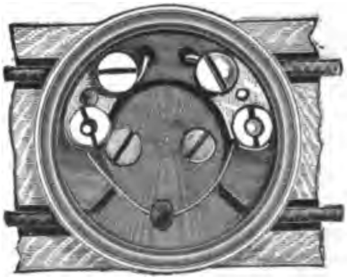
The best work in this field has been performed by Mr. A. C. Cockburn, whose fuse is illustrated in fig. 302. The wire is of pure tin, a leaden shot is cast on at the middle of the wire, and its extremities terminate in small contact rings. These rings are slipped over the terminal screws, and the nut being tightly screwed down reliable contact is ensured. The distance between the screws is such that the sag of the wire is about equal to that shown in the figure, and immediately the current becomes strong enough to develop sufficient heat to soften the wire, the weight of the leaden shot causes a prompt and decided break. The disconnection thus occurs long before the temperature is reached at which the metal would become red hot, and before dry wood would ignite or even char. The cases in which these fuses are fixed are usually made of hard wood, or of slate or porcelain for the base with a brass cover attached by a bayonet joint. In some instances a wooden case lined with asbestos and fitted with a glass cover is employed, the great advantage being that the fuse can easily be inspected, so that when a number are in use it can quickly be ascertained which particular one it is that requires to be renewed. The rings at the ends of the wire enable the replacement to be effected with ease and rapidity, and they have the further advantage that they preclude any uncertainty as to the length of wire actually in use. Since the capacity of the terminal screws for conducting away the heat affects the result, the fuse should only be employed in the particular type of case for which it has been designed.

FIG. 302.



For heavy currents several comparatively small fuses are joined in parallel, instead of employing a massive wire, an arrangement which makes more certain the breaking of the fuses when the particular current strength is exceeded.

FIG. 303.

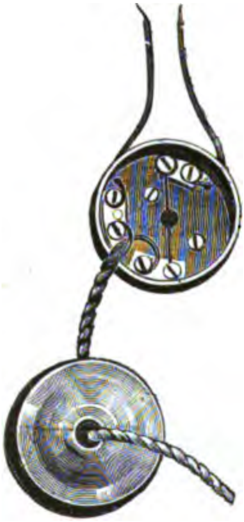


In fig. 303 is shown one of the simple fuses placed in position, the cover of the case being removed. The ends of the upper lead are brought up through holes in the slate base, one to each of two fixed brass strips, the fuse itself being connected to other terminal screws on the same strips. The case can if required be placed horizontally.

Many other types of cut-outs are in use, some consisting of wire, and others of thin foil of various metals, but that described is probably the best for general work, and is sufficiently inexpensive to allow of one being placed in circuit with every incandescent lamp in any installation.

An illustration of a method by which a cut-out may be applied to protect a single lamp is furnished by fig. 304, which shows a ceiling-rose, or a device for placing a lamp in circuit between a pair of leads carried along a ceiling, and suspending a lamp therefrom. The wires from the leads enter through holes in the back of the apparatus, and are connected each to a small brass block or strip, one of which is also connected to one lamp terminal and the other to one end of the safety fuse. The other end of the fuse and the other terminal of the lamp are joined to a third brass block. The flexible double wire by which the lamp is suspended is threaded through a hole in the centre of the cover, which screws on to the base.

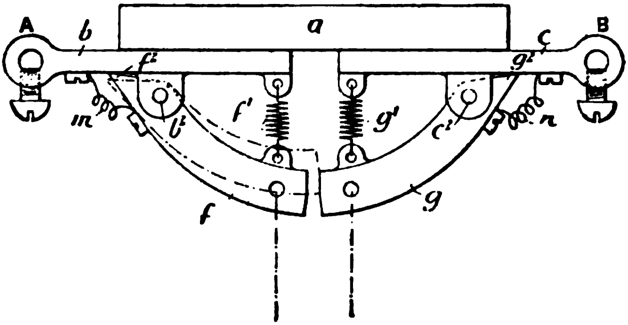
FIG. 304.



One possible objection to the use of a fuse is that when it does act under the influence of a too powerful current it is destroyed, breaks the circuit of the lamp or lamps, and must be replaced before the circuit is again available. It will be evident that such cut-outs must be cheap, placed in accessible situations, be easily replaceable, and be confined in an infusible or non-inflammable case.

The cut-outs which we have thus far described are intended as a safeguard against the maintenance of an excessive current, such as might be caused by the short-circuiting of a lamp, and they are more particularly applicable to constant potential, or parallel working. When, however, a series circuit is fitted up, the danger to be guarded against is rather a disconnection than a short circuit, for should the filament of a single lamp, or any one of the conducting wires be broken, the current through the others will also be interrupted. We have already described (in the preceding chapter) a few protecting devices for the lamps themselves, but none capable of affording protection in the case of a complete smash of a lamp have been dealt with. Mr. A. A. Goldston has introduced a simple but ingenious contrivance for maintaining, under almost *all* circumstances, the continuity in a series circuit consisting of a number of suspended lamps. The device is illustrated in fig. 305, and is intended to short circuit the suspending wires of any lamp in the event of one or both of those wires breaking, or if from any other cause the weight on either of the wires is reduced.

FIG. 305.



A and B are the two main terminals which are attached to the brass pieces f^2 g^2 which are fixed on the insulating base a. The conducting spirals m n serve to connect the screws b c to another pair of screws on the contact-making levers f g. These levers are able to turn through a small angle on the pins b^2 c^2 and are supported by the spiral springs f^1 g^1. The wires by which the lamp is suspended are attached one to f and the other to g, the weight of the lamp sufficing to keep f and g apart. Should one of the wires, say that attached to f, break, the tension is reduced, and the corresponding spring f^1 is allowed to act, drawing f into the position indicated by the dotted lines and completing the circuit through the two pivoted levers direct. The device is also applied to arc lamps, and can be fitted in incandescent lampholders so as to maintain the circuit in the event of a disconnection at the platinum loops or in any portion of the holder. The spiral springs are in the actual apparatus provided with adjusting screws, by which their tension can be regulated so that were even the bulb broken this slight reduction of the weight would allow the springs to raise the levers. The arrangement effectually provides also for the case of a complete smash of the lamp, such as might destroy the short-circuiting device inside the lamp itself. Under ordinary circumstances a short-circuit between, or a fracture of either of, the suspending wires might initiate an arc, which would then probably travel up the wires and possibly start a fire. The device under notice prevents the maintenance of such an arc, because immediately the wire is fused and the weight removed the two conductors are cut out of circuit.

The apparatus is made in a variety of forms, but an advantage pertaining to the one illustrated is that the contact surfaces being vertical do not permit the accumulation of dust or dirt. The potential difference available in a series circuit is, however, sufficient to strike across even a considerable film of imperfectly conducting particles. It will be evident that to make this apparatus most efficient, it is better to use two separate instead of twisted conductors.

In a previous chapter we have described certain instruments called ammeters, which are capable of indicating the number of amperes of current flowing through them at any particular moment, but which are unable to measure the actual quantity of electricity passed through them during any given time. In just the same way a thermometer indicates the temperature at any moment, but gives no idea of the quantity of heat actually developed or absorbed. In the commercial distribution of electricity for lighting or other purposes, it is essential that a 'meter' should be provided which is capable of measuring and by some means recording the quantity of electricity supplied to any one consumer during say a month or three months. The unit quantity of electricity is the coulomb, that is the amount transferred by a current of one ampere during one second; hence an instrument such as that referred to might aptly be called a coulomb-meter.

The coulomb is, however, too small for electric lighting work, and it has been usual to employ as a unit the quantity of electricity transferred by a current, one ampere in strength, during one hour, this unit being known as the 'ampere-hour.' If, for example, a secondary cell were allowed to maintain a current of 15 amperes for 2½ hours, the *quantity* of electricity obtained from the cell during that time would be $15 \times 2{\cdot}5 = 37{\cdot}5$ ampere-hours. But even this larger unit is somewhat small for the measurement of supply on an extensive scale. We have already mentioned the kilowatt as the practical unit of power, sometimes referred to as the Board of Trade unit of power. The Board of Trade unit, properly so-called, is a commercial unit of electrical energy, and is equal to that amount which is developed or absorbed by a current of 1,000 amperes at a pressure of one volt during one hour. It is therefore equal to 1,000 ampere-volt-hours.

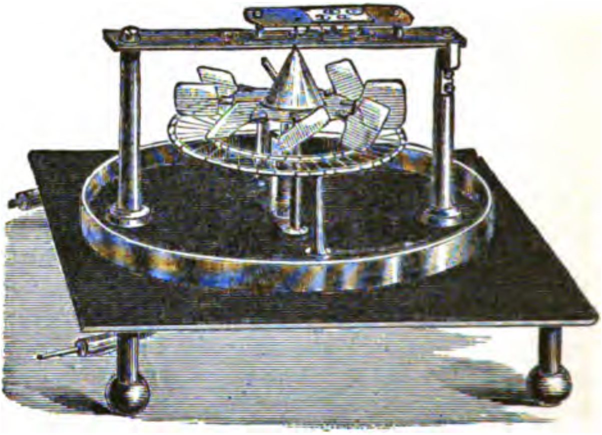
This Board of Trade unit is, then, the unit by which the electricity supplied is measured and charged. Under ordinary circumstances some piece of apparatus is introduced to indicate the number of ampere-hours supplied to the consumer's lamps, and this quantity multiplied by the pressure in volts and divided by 1,000 gives the number of Board of Trade units upon which the charge is based. But it is unfortunately far from easy to measure a quantity of electricity satisfactorily on a commercial scale. In fact the instrument most urgently needed in the electrical world at the present moment is a simple, reliable, and compact quantity meter.

Many efforts have been made to produce such an instrument, and although some practical forms have been brought into use, much yet remains to be done by the usual process of development.

The simplest in principle, and perhaps also the most interesting, is that devised by Professor Forbes. It is based upon the heating effect of the current; the instrument can therefore be made without any appreciable self-induction, and is consequently available for use with alternating currents.

The apparatus is illustrated in fig. 306. It consists of two concentric copper rings, supported at a little distance above the base and bridged across by a number of short fine wires. The current enters at one ring and leaves it by the other, passing through the whole of the fine wires in parallel, the resistance offered by the wires being about $\frac{1}{100}$th of an ohm. The quantity of heat developed in these wires affords the means of estimating the quantity of electricity which passes. When the wires become warm the heat is imparted to the adjacent air, which expands and rises, so that a continual upward current of air is maintained during the whole time that the current is flowing, the strength of the air-current varying of course with the extent to which the wires are heated. A small pillar carrying a steel needle point rises through the centre of the rings, and a thin paper cone with a ruby bearing at its apex rests on the needle point. The base of the paper cone is attached to a small horizontal mica disc, from the edge of which project eight arms made of pith, each carrying a very thin mica vane, inclined at an angle of 45° to the horizontal, and placed directly over the fine cross wires.

FIG. 306.



The ascending air currents caused by the passage of electricity strike against the under side of the vanes, and cause them and the paper cone to rotate; the stronger the current of electricity the more powerful are the air currents and the greater the number of revolutions in a given time. So that it is only necessary to add some device for recording the number of revolutions in order to estimate the quantity of current which has flowed.

The apex of the paper cone consists of a small aluminium cone (to which is attached the ruby bearing above referred to) and which also carries above the apex a small steel pinion, gearing into a train of wheels as shown in the figure. The train records the number of revolutions in the ordinary manner; but it will readily be apparent that since the force which causes the rotation is so feeble, the slightest friction would be inadmissible, and the whole of the moving parts must be extremely light and delicate. In fact, beautiful as the principle is, it is to be feared that it would be difficult to develop it into a thoroughly practical instrument.

A quantity meter also based upon an interesting principle, and which in spite of many difficulties is being brought into a practical form, is that of Mr. Ferranti. We know that a conductor when placed in a certain position in a magnetic field is urged to a new position in, or entirely out of, the field, immediately a current is passed through the conductor. If any portion of the conductor is movable independently of the remainder, we can move that portion only by sending all or nearly all of the current through it. A somewhat striking case is that of a liquid conductor such as acidulated water or mercury, for we can keep the liquid continually in motion by placing the containing vessel in a powerful field, and sending a current through the liquid. If the lines of force of the field and those emanating from that portion of the liquid which is carrying the current do not happen to coincide, then that portion will be urged to a new position just as a copper wire would be, its place being taken by more of the liquid, which undergoes a similar treatment.

In Mr. Ferranti's meter, which is based upon this principle, the liquid employed is the purest obtainable mercury. This is contained in a rather shallow circular vessel, above which is placed a solenoid fitted with a hollow iron core and a sheath, so disposed as to project a very powerful field vertically through the mercury. The current is led to the mercury at the centre of the vessel, and leaves it at the circumference, then passing through the magnetising solenoid.

Now the liquid conductor is urged to move in a direction at right angles to that in which the current is flowing through it, and also at right angles to the lines of force of the field. The direction of the current is radial, and supposing the lines of force to be projected vertically downward, the liquid will rotate in a right-handed direction as viewed from above. The force with which the mercury is urged to rotate is proportional to the strength of the current flowing through it and to the strength of the fixed field. This field might be kept constant; or by employing the same current to excite the solenoid, and never allowing the iron to approach the saturation point, the field may be made to vary with the current, when the force tending to produce rotation will be proportional to the square of the current.

The mercury in rotating carries with it a light delicate float, which is attached to the lower end of a light rod terminating at its upper extremity in a pinion which gears into a wheel forming part of the mechanism employed to indicate the number of revolutions made by the float. Of course the force acting is very small, and any appreciable friction would seriously affect the indications, but it appears probable that the difficulties will be overcome and the instrument brought into practical use.

The meter which, up to the present, has been most extensively employed is based upon the electrolytic properties of the current, and possesses the advantage that no delicate mechanism need be employed in connection with it. When a current is passed through a solution containing a metal, such as nitrate of silver or sulphate of copper, the solution is decomposed and the metal which it contained is deposited on the wire or strip of metal by which the current *leaves* the liquid. Such a wire or strip by which the current leaves or enters the liquid is called an electrode. Suppose, for example, a solution of nitrate of silver with silver electrodes to be employed, then pure silver would be deposited from the solution upon that electrode by which the current leaves. Moreover, an exactly equal quantity of silver would be dissolved from the other electrode; this might easily be proved by weighing before and after the passage of a current, for it would be found that the one had lost in weight just as much as the other had gained. The solution, then, remains as rich in metal as it was before the passage of the current; but if the electrode by which the current enters were made of carbon, or an unassailable metal like platinum, the solution would lose just as much metal as is deposited on the other electrode, the platinum not being dissolved at all.

It is a most important fact that the weight of metal deposited in this manner is exactly proportional to the quantity of electricity which has passed through the solution, irrespective, within wide limits, of the density of the solution, or the strength of the current at any part of the time. It follows that after having ascertained the weight of any metal which is deposited by a coulomb of electricity, or by an ampere-hour of electricity, we can always calculate exactly the quantity of electricity which has been transferred on any occasion, provided we find out what weight of that metal the current has deposited. Now the solutions which concern us most at present are nitrate of silver, sulphate of zinc, and sulphate of copper, and it has been found by experiment that one coulomb (or ampere-second) is capable of depositing from these solutions 1·118 milligramme of silver, 0·33696 milligramme of zinc, and 0·32709 milligramme of copper respectively. The ampere-hour, being 3,600 times greater than the coulomb, deposits 4024·8 milligrammes of silver, 1213·056 milligrammes of zinc, or 1177·524 milligrammes of copper. So long as the total quantity of current which passes is the same, it is immaterial whether the deposition is effected by a weak current flowing for a long time or a stronger current flowing for a correspondingly shorter time. Thus a current of half an ampere flowing for 48 hours will deposit the same weight of copper as a current of 16 amperes flowing for 1½ hour; in either case the total quantity of electricity is 24 ampere-hours. It is necessary, however, to take care that the surface of the electrode shall be ample, otherwise the metal is deposited so rapidly on a small surface that it becomes granular, and does not adhere.

Now suppose we take a vessel containing a solution of zinc-sulphate, and dip into the solution two zinc strips which have been accurately weighed. If, by suitable connections, we insert this arrangement in one of the main leads of an electric light circuit, zinc will be dissolved from one electrode, and an equal amount deposited on the other whenever a current is passing. If at the end of a month the plates are removed, carefully dried, and weighed again, the total amount of electricity which has during that period been supplied to the lamp circuit can be very accurately estimated. Slight impurities and local actions may in practice prevent the gain of the one being exactly equal to the loss of the other, but by weighing them both and taking the mean of the loss and gain, a more reliable result can be arrived at. As a rule, however, only the loss on the plate by which the current enters the cell, is taken as a measure of the quantity of current which has passed. Suppose this loss amounted to 1,213 grammes, then the quantity of electricity upon which to base the charge would be 1,000 ampere-hours.

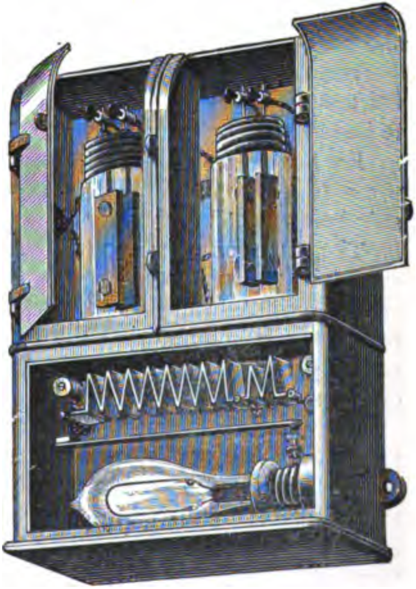
The 'chemical' meter of Edison is constructed upon this principle, and it will be as well to point out a few of the possible sources of trouble and inaccuracy in the simple arrangement just mentioned, before describing the latest form of the meter.

The cell offers some resistance to the passage of the current, depending upon the size of the plates and their distance apart; in order to allow it to be placed directly in an ordinary electric light main the size of the plates would have to be unduly large. It is necessary, therefore, to use the cell as a shunt, bridging over a short portion of the main circuit having a resistance equal to say $\frac{1}{999}$ of its own; in that case the meter measures $\frac{1}{1000}$ of the total current flowing.

But then temperature variations alter the resistances sufficiently to cause grave errors in the results. A rise in temperature, for instance, reduces the resistance of the liquid, but increases that of the portion of the main conductor which is shunted by the cell. Both these effects tend to cause an increase in the proportion of the current flowing through the meter, and such variations must in some way be compensated for.

Moreover, the temperature may fall low enough to freeze the liquid. Also since any external cause which cools the liquid or the shunted metallic conductor, or both, makes the meter register lower than it should do, care must be taken to so place these parts as to avoid leading the consumer into temptation. For similar reasons the terminals of a meter should never be exposed, nor any other facilities given for short-circuiting the apparatus.

FIG. 307.



The practical form of the Edison meter, as fitted for use in a simple circuit, and in which these difficulties are overcome, is illustrated in fig. 307. At the bottom of the case is an incandescent lamp, which is automatically thrown into circuit whenever the temperature approaches the freezing point, and so keeps the solution from freezing. Above the lamp is placed a stout zigzag strip of German silver, which is joined up in the main circuit. It offers but little resistance, and since its temperature coefficient is small, this resistance varies but slightly through ordinary changes. Above this strip two cells are placed, each containing two zinc plates immersed in a sulphate of zinc solution. The zinc is deposited at a definitely faster rate in one cell than in the other, and an additional check obtained by comparison of the two cells. The difference in the rate of deposition is effected by causing one cell to bridge a larger portion of the German silver strip than the other; the dividing terminal is seen in the figure at the end of the second bend from the right. The most important of the possible sources of error is that due to the temperature variation of the resistance of the liquid. This is compensated for and the resistance of the cell circuit kept constant in a very simple manner. When the temperature rises the resistance of the liquid *decreases*, but the resistance of a metal (copper for instance) *increases*. A spiral of copper wire is joined in series with each cell, of such a resistance that with a given rise in temperature the resistance of the spiral increases by just so much as the resistance of the liquid is decreased. These spirals are placed behind the cells and are not visible in the figure.

In the smaller meters (and latterly in larger ones) only one cell is employed, the resistance of the German silver strip being about 0·003 ohm.

The meter is placed in the circuit of one of the mains feeding the group of lamps in which the electricity consumed is required to be measured.

For installations on the three-wire system two separate German silver strips with a cell or a pair of cells to each are provided, one strip being placed in each main.

The variation of the resistance of the German silver strip caused by temperature changes is not sufficient to introduce any great error. As a rule its resistance is $\frac{1}{999}$ that of the cells and compensating wire, so that the cell measures $\frac{1}{1000}$ of the total current passing through the main circuit. The plates are weighed once a month.

The method of throwing the heating lamp in circuit when the temperature falls too low is simple and ingenious. One terminal of the lamp is connected to one of the mains, and its other to a small contact stud placed just above the holder. Above this stud is another contact, carried at the end of a long straight compound metal strip, which is fixed at the other end (to the left in the figure) and connected to the other main. The strip is formed of two metals, which expand or contract unequally when the temperature is varied. Under ordinary circumstances the two contact studs are kept apart; but when the temperature falls, the compound strip bends or curls downward, and the adjustment is such that contact is made and the lamp thrown in circuit when the temperature approaches within two or three degrees of freezing point.

INDEX

[Every dash (—) stands for a word in the line preceding it.

ACCUMULATORS. *See* Secondary Cells
Acid solution for secondary cells, density of, 480
Acidometers, 481
Action, local, 60
Adjacent conductors, mutual action between currents in, 82, 402, 446, 617
Adjustment of brushes, 288, 407
Air pump, mercury, Geissler, 535
— — — heated, 554
— — — short-fall, 544
— — — Sprengel, 537
— — — Swinburne, 542
— pumps, 535
— — mechanical, as an aid to mercury pumps, 538
— — mercury, device for arresting mercury vapour, 539
— — — Gimingham, 539
— — — McLeod's pressure-gauge for, 540
— — — objections to simple, 538
Alternate current dynamos, 230
— — — De Meritens, 248
— — — Ferranti, 258
— — — Kapp, 252
— — — Mordey, simple form, 245
— — — Mordey-Victoria, 264
— — — Siemens, 255
— — — Wheatstone, 244
— — — with rotating field, 264
— — motors, 438
— — — method of starting large, 438
Alternating and continuous current arc lamps, 505
Alternating currents, apparatus for measuring, 114, 126
— potential differences, apparatus for measuring, 179, 200
Alternation, rate of, in transformers, 455
— — — — Mordey's experiments, 456
Alternators. *See* Alternate Current Dynamos
— in parallel, 269, 439
— — — Mordey's experiments, 439
— used as motors, 438
Amalgamation, 62
Ammeter, Ayrton and Perry, 115
— eccentric iron disc, 128
— Evershed, 122

Ammeter, graded, Sir W. Thomson, 118
— Schuckert, 120
— Société des Téléphones, 127
— steel-yard, 127
Ammeters, electro-magnetic, 120
— gravity, 120
Ampere, the, 22
Ampere-hour, 615
Ampere-turns, 125, 206, 295, 350
Ampere-yards, 206
Angle of lead, 286, 353, 407
Arc, consumption of carbons, 494, 523
— counter E.M.F. of the, 498
— Davy's experiments, 492
— disintegration of carbons, 495
— formation of carbons, 493
— impurity of carbons, 497
— temperature of carbons, 495
— volatilisation of carbons, 497
— lamp, Brockie-Pell, 519
— — Brush, 511
— — Crompton and Crabb, 515
— — Gülcher, 505, 523
— — Jablochkoff, 501
— — Phœnix, 518
— — Pilsen, 506, 507
— — Statter, 521
— — Werdemann, 503
— lamps, 492
— — alternating and continuous current, 505
— — c.p. per h.p., 500
— — classifications of, 503
— — differential, 505, 506
— — effect of globes, 500
— — feeding arrangements, 505
— — for focussing, 504
— — parallel and series, 503
— — steadying resistance, 504
Armature coils in parallel, 275
— core, lamination of, 242
— — effect of, 274
— cylinder form, 317
— drum, 289
— Gramme, 283
— — as a transformer, 451
— losses in, 375
— — — Mordey's experiments, 376
— magnet, effect of, 92
— open-coil, 381

Armature, ring, 283
— shuttle, 240
Atomic weights and equivalents, table of, 45
Attractive power of electro-magnets, 221
Automatic alarum for secondary cells, 490
— switch for Jablochkoff lamp, 502
— — — secondary cells, 489
Available E.M.F. in external circuit of batteries, 79
Ayrton and Perry's ammeter, 115
— — dispersion photometer, 572
— — low-reading voltmeter, 190, 461

Bare conductors, 579, 595
Batteries, available E.M.F. in external circuit of, 79
— counter E.M.F. in, 466
— fall of potental in, 80
— primary, 43
— secondary. *See* Secondary Cells
Battersea dynamo, 373
Battery, floating, 85
— gas, 467
— mud, 59
Beam of light, 495, 572, 573
Bernstein lamp, 551
Bichromate of potash cells, 55, 68
Bitumen insulation, 598
Blackpool Electric Tramway, 418
Blower, Thomson-Houston, 397
Board of Trade unit, 615
Boiling, in secondary cells, 479
Bridge, slide wire, 147
— Wheatstone, 143
— — dial form, 157
— — practical form, 148
— — — — galvanometer for, 156
— — — — method of using, 150
Britannia joint, 593
Brockie-Pell lamp, 519
Brooks' system, 596
Brush dynamo, 383
— lamp, 511
— regulator, 389
Brushes, adjustment of, 288, 407
— Holroyd Smith, 412, 423
— sparking at, 288, 353
— with carbon contacts, 412, 416
Buckling, 483
Bunsen cell, 67
— photometer, 570

C.G-S. system, 41
Cables, lead covered, 600, 601
Calibration, 113
Callender's bitumen system, 598
Candle, the standard, 557
Candle-power of arc lamps, 500
— — Jablochkoff lamp, 501
Capacity of secondary cells, 485
— for heat, 179
Carbon, manufacture of, 499
— properties of, for incandescent lamps, 528
— resistance of, 499

Carbon resistances, 389
Carbonising, 532
Carbons, arc, consumption of, 494, 523
— — disintegration of, 495
— — formation of, 493
— — impurities of, 497
— — temperature of, 495
— — volatilisation of, 497
Carcel lamp, 561
Casing, wood, 602
Cast and wrought iron for field magnets, 254
Ceiling rose, 612
Cell, agglomerate, 47
— bichromate of potash, 55
— Bunsen, 67
— Clark standard, 53, 108, 163, 175, 435
— Daniell, 56
— — standard, 64, 108, 164
— definition of constant, 47
— — — primary, 43
— Faure, 472
— Fuller, 68
— Grove, 65
— Leclanché, 47
— Muirhead-Daniell, 63
— Planté, 469
— simple, 2, 43
— Smee, 46
— Upward, 69
— zinc-carbon, 47
Cells, comparison of, 73
— consumption of zinc in, 79
— economical grouping of, 79
— methods of grouping, 75
— secondary. *See* Secondary Cells
— substitution of, formulæ for, 81
— testing condition of, 169
Characteristic curves, 304
Charging curve for secondary cells, 479
Chemical reactions in secondary cells, 477
Circuits, parallel, 24, 138
Classifications of arc lamps, 503
Cockburn fuse, 610
Coercive force, 218
Coils, induction, 446
Collecting currents from moving conductor, method of, 239
Collectors. *See* Commutator
Colours of secondary plates, 481
Commutation, 270, 367, 381
Commutator, 270, 367, 381
— Battersea, 374
— Brush, 385
— Edison-Hopkinson, 337
— eight-part, 280
— four-part, 277
— Goolden, 321, 412
— Kapp, 335
— Manchester, 344
— open-coil, 381
— Paris and Scott, 350
— Phœnix, 330
— Statter, 362, 364
— Thomson-Houston, 393
— three-part, 393
— two-part, 271
— Victoria, 367
Comparison of cells, 73

Comparison tests for E.M.F., 164
Components of terrestrial magnetism, 94
Compound dynamo, the, 303, 313
— — curve for, 312
Condition of cells, testing, 169
Conductivity, electro-magnetic, 87
— of commercial copper, 18
Conductors and non-conductors, 9
— bare, 579
— cost of laying, 578
— fall of potential in, 581
— for heavy currents, 576
— indoor, 602
— loss of energy in, 444, 577
— overhead, 588
— table of, 578
— underground, 419, 429, 595
Conduit, Northfleet, 428
— Pall Mall, 595
Conduits, Holroyd Smith's, 418, 427
Conservation of energy, 88
Constant cell, definition of, 47
Constant current dynamos, 352, 389, 395
— — regulation, Brush, 389
— — — Goolden, 325
— — — Statter, 352
— — — Thomson-Houston, 395
Consumption of carbons in the arc, 494, 523
— — zinc in cells, 79
Continuous and alternate current arc lamps, 525
Conversion of electricity into heat and light, 526
— — — — mechanical power, 402
Copper, conductivity of commercial, 18
Core of electro-magnet, 214
— — — dimensions of, 219
— iron, 87
— ring, leakage of lines of force across a, 283
Coulomb, the, 22
Counter E.M.F. of the arc, 498
— — in batteries, 466
— — — motors, 404
Couple, moment of a, 96
Couples, 95
Crompton dynamo, 351
— and Crabb arc lamp, 513
Crookes's device for arresting mercury vapour, 539
Cruto lamp, 556
Current, nature of a, 3
Current-density, 487
Current-strength, 21
— — measurement of, 82, 435
— — practical unit of, 22
Currents, apparatus for measuring alternate, 114–126
— apparatus for measuring large, 109
— eddy, 241, 375, 450, 457
— galvanometers for weak, 170
— in adjacent conductors, mutual effects of, 82, 402, 446, 617
— lines of force developed by, 83
Curve, charging, for secondary cells, 479
— discharging, for secondary cells, 482
— external characteristic, 308
Curve of compound dynamo, 312
— — series dynamo, 305
— — shunt dynamo, 310
Curves, characteristic, 304
— E.M.F., 278
— horse-power, 306
— magnetisation, 214
Cut-out for series incandescent lamp, Bernstein, 552
— — — — — — — Edison, 555
— — — — — — — Goldston, 555, 613
Cut-outs, 609

DANIELL cell, 56
— — Muirhead's form, 63
— — standard, 64, 108, 164
De Meritens alternator, 248
Declination, magnetic, 94
Density, current, 487
Density of acid solution for secondary cells, 480
Detector, lineman's, 128
Differential arc lamp, the, 505, 506
— galvanometer, 138
Diffusion of liquids, 59
Dip, magnetic, 94
Direct-current dynamo, Battersea, 373
— — — Brush, 383
— — — Crompton, 351
— — — Edison, 336
— — — Edison-Hopkinson, 336
— — — Goolden, 317
— — — Kapp, 332
— — — Manchester, 343
— — — Paris and Scott, 347
— — — Phœnix, 328
— — — Statter, 352, 432
— — — Thomson-Houston, 391
— — — Victoria, 364
Direct-current dynamos, 270
Direction of lines of force, 84
Discharge, electric, 3
Discharging curve for secondary cells, 482
Dispersion photometer, 572
Distortion of field, 285, 407, 417
Distribution, 579
— by transformers, 461
Drake and Gorham's experiments with secondary cells, 479
Drum armature, the, 289
Dynamo, compound, 303, 313
— — curve of, 312
— limitation to power developed by, 296
— power absorbed by, 297, 350
— series, 295
— — curve for a, 305
— — regulation of a, 299
— shunt, 300
— — curve for a, 310
— small, with steel magnets, 239
Dynamos, alternate current. *See* Alternate Current Dynamos
— direct current. *See* Direct Current Dynamos
— efficiency of, 230, 302
— experiments with, 316, 339, 352, 345, 375, 433

Lead-covered cables, 600
Leak in secondary cells, effect of, 483
Leakage, magnetic, 222
— — in dynamos, 339, 345
— in transformers, 464
— of lines of force across a core-ring, 283
Leclanché cell, 47
— — agglomerate form, 47
Legal ohm, 13
Letheby photomoter, 574
Life of incandescent lamps, 545, 550
Light, beam of, 495, 572, 573
— analysis of, 495
— measurement of, 557
Light and heat, conversion of electricity into, 526
Line of force, C.G.S., 93, 281
— Kapp, 336, 350
Lineman's detector, 128
Lines of force across a core-ring, 283
— — — developed by a current, 83
— — — electric, 4
— — — iron cannot increase the number of, 88
— — — through a magnet, 89
— — — through iron, 86
Liquids, diffusion of, 59
Lithanode, 486
Local action, 60
Loop test, 154
Loss of energy in conductors, 444, 577
Losses in armatures, 375
— — — Mordey's experiments, 376
Low-reading voltmeter, 190, 461
Luminous bodies, 496
— rays, proportion of, 573

MACHINES, dynamo electric. *See* Dynamos
Magnet, lines of force through a, 89
— permanent, 217
— — armature of, 92
— — effect of heat upon, 219
— — — — vibrations upon, 218
— — field of force due to, 90
— — sustaining power, 219
— pole, of unit strength, 93
— the earth a, 93
Magnetic cut-out, 609
— declination, 94
— dip, 94
— force, earth's total, 94
— leakage in dynamos, 339, 345
Magnetisation curves, 214
Magnetism, residual, 296
— terrestrial, components of, 94
Magnets, field, wrought and cast iron for, 294
— mutual effects between, 92
Mains, underground, 419, 429, 595
Manchester dynamo, 343
Manufacture of electric light carbons, 499
— — incandescent lamps, 531
Marriage joint, 600
McLeod's pressure-gauge, 540
Measurement of current strength, 82
— — electro-motive force, 163
— — light, 557
Measurement of luminosity of electric lamps, 573
— — resistance, 131
Measuring alternating currents, apparatus for, 114, 126
— alternating potential differences, 179, 200
— large currents, apparatus for, 109
Mechanical power, conversion of electricity into, 402
Megohm, the, 13, 160
Mercury pumps. *See* Air Pumps
Meritens, De, alternator, 248
Metals, expansion of, by heat, 179
— for incandescent lamp filaments, 528
Meters, 614
Methven screen, 561
Mica, 321
Microhm, the, 13
Mordey alternator, 264
— — simple form, 245
— experiments on losses in armatures, 376
— — with alternators in parallel, 439
— — — transformers, 456
— method of starting alternate current motors, 438
— transformer, 454
Motor coils, heating of, 417
— distortion of field in a, 407, 417
— Goolden, 411
— Holroyd Smith, 423
— Immisch, 416
— methods of varying strength of field in a, 409
— rate of working in a, 411
— regulation, 408
— Sprague, 414
Motors, 230, 402
— alternate current, 438
— efficiency, 411, 433
— in parallel and series, 428, 432
— switches for, 426, 431
Mounting filaments, 534
Mud battery, 59
Muirhead-Daniell cell, 63
Multipolar dynamos, 364

NATURE of electric current, 3
— — electricity, 4
Non-conductors and conductors, 9
Northfleet Electric Tramway, 428

OBJECTIONS to simple mercury pumps, 538
Ohm, the legal, 13
Ohmmeter, Evershed, 159
Ohm's law, 22, 74, 105, 131, 163
Open-coil armatures, 381
— — dynamo, Brush, 383
— — — Thomson-Houston, 391
— — dynamos, 380
— — — commutator for, 381
Opposition method of testing E.M.F., 167
Output of secondary cells, 489
Overhead conductors, suspension of, 593
— system, 588

PACINOTTI teeth, 348, 362
Parallel, alternators in, 269, 439
— and series arc lamp, 503
— — — incandescent lamps in, 551
— — — motors in, 428, 432
— — — transformers in, 461
— armature coils in, 275
— circuits, 24, 138
— working, 580
Parallelogram of forces, 94
Parchmentising, 531
Paris and Scott dynamo, 347
Pentane lamp, 566
— standard, 564
Permanent magnets. *See* Magnets
Permeability, 202
Phœnix dynamo, 328
— lamp, 518
Photometer, Ayrton and Perry's dispersion, 572
— Bunsen grease-spot, 570
— Hartley universal, 574
— Letheby, 574
— Rumford shadow, 569
Photometers, 569
Photometry, 557
Pilot-wires, 582, 602
Pilsen lamp, 506, 507
Planté cell, 469
Plates, expansion of secondary, 484
Platinoid, 16
Platinum, melting-point of, 610
Plugs, necessary features of, 32
Point, saturation, 115, 214
Polarisation, 46, 466
Pole, strength of magnet, 93
Poles for overhead work, 589
Positive direction of lines of force, 84
Potential, 5
— difference, 13
— — alternating, apparatus for measuring, 179, 200
— fall of, in a battery, 80
— — — — conductors, 581
Potentiometer, 175
Power absorbed by dynamo, 297, 350
— developed by dynamo, limitations to, 296
— waste of, in conductors, 577
Practical unit of current quantity, 22, 614
— units, 12
Preece, W. H., on secondary cells, 487, 488
Pressure-gauge, McLeod's, 510
Primary batteries, 43
Primary cell, definition of, 43
Proportion of luminous to other rays, 573
Pumps. *See* Air Pumps

QUANTITY meters, 614
— practical unit of current, 22, 614

RATE of alternation in transformers, 455
— — working in a motor, 411
Regulation by secondary cells, 488, 582, 583
Regulation constant current, 325, 352, 389, 395
— motor, 408
— of series dynamo, 299
— — transformers, 461
Regulator, Brush, 389
— Goolden, 323
— Thomson-Houston, 395
Residual magnetism, 290
Resistance, 13
— boxes, 31
— coils, 28
— effect of heat upon, 18
— — — impurities upon, 17, 579
— frames, 36
— fundamental laws, 19
— insulation, 158, 597
— internal, of battery, 74, 135
— measurement of, 131
— — — differential method, 141
— — — internal, 136, 137
— — — — of secondary cells, 138
— — — substitution method, 133
— — — with tangent galvanometer, 134
— — — — Wheatstone bridge, 143
— of carbon, 499
— specific, 16, 17
— steadying, for arc-lamps, 504
Retentivity, 89, 216
Return, earth, 6, 420
Rheostat, 34
Ring armature, Gramme, 283
— switch, 604
Rumford shadow photometer, 569

SAFETY devices for transformers, 462
Saturation-point, 115, 214
Scale, tangent, 102
Schuckert ammeter, 120
Screen, Methven, 561
Secondary cells and batteries, 466
— — applications of, 487
— — automatic alarum for, 490
— — — switch for, 489
— — boiling in, 479
— — buckling of plates in, 483
— — capacity of, 485
— — charging curve for, 479
— — chemical reactions in, 472
— — colour of plates in, 481
— — current density, 487
— — density of solution, 480
— — devices for fixing pastes, 473
— — discharging curve for, 482
— — Drake and Gorham's experiments, 479
— — durability of plates, 484
— — efficiency, 486
— — Elwell Parker type, 477.
— — E.M.F. of, 479
— — E.P.S. types, 474
— — — — table of, 477
— — expansion of plates, 484
— — hydrometers for, 481
— — insulators for, 475
— — leakage, effect of, 483
— — output of, 489

Secondary cells, Preece, W. H., on, 487, 488
— — regulation by, 488, 582
— — step-by-step switch for, 607
— — sulphating in, 483
— — treatment of new, 483, 486
Self-induction, 227, 241, 353, 440, 463
Semi-incandescent lamps, 503
Sensitiveness, angle of maximum, 108
Series and parallel arc lamps, 503
— — — incandescent lamps in, 551
— — — motors in, 428, 432
— — — transformers in, 461
— circuit cut-out, 552, 555, 612
— dynamo, 295, 314
— — curve for, 305
— — limitations to power developed by, 296
— — power absorbed by, 297, 350
— — regulation of, 299
— lamps, incandescent, 551
— — cut-outs for. *See* Cut-outs
Shackle insulator, 592
Shadow photometer, 569
Shape of electro-magnets, 222
Short-fall pumps, 544
Shunt box, 35
— dynamo, 300
— — curve of, 310
Shunts, law of, 106
Shuttle armature, 240
Siemens alternator, 255
— electric dynamometer, 110
Simple alternator, 239
— — Mordey's, 245
— cell, 2, 43
— transformer, 450
Sine curve, 237
Sines and tangents, table of, 98
Slide wire bridge, 147
Smee cell, 46
Smith's, Holroyd, tramway system, 418
Société des Téléphones ammeter, 127
Solenoid, field due to a, 87
— iron in a, effect of, 87, 121, 122
Sparking at brushes, 288, 353. *See also* Distortion
Specific heat, 179
Spectrum, the, 496
Spirals, flat, effects between, 85
Splayed joint, 594
Sprague motor, 414
Sprengel pump, 537
Spring, flat, ammeter, 116
Squared paper, 214
Standard candle, the, 557
— cell, the Clark, 53, 108, 163, 175, 435
— — the Daniell, 64, 108, 164
— the pentane, 564
Statter current regulation, 352
— dynamo, 352, 432
— lamp, 521
— transformer, 457
Steadying resistance for arc lamps, 504
Steel, magnetic effect of impurities in, 217
— yard ammeter, 127
Strength of magnet-pole, 93
Substitution of cells, formula for, 81

Sulphating, 483
Summary (on dynamos), 398
Suspension of overhead conductors, 593
Sustaining power of magnets, 222
Swan lamp, 530
Swinburne pump, 542
Switch, automatic, for Jablochkoff lamp, 502
— — — secondary cells, 489
Switches, 602
— for motors, 426, 431
System, Brooks', 596
— C.G.S., 40
— overhead, 588
— three-wire, 585, 595
— underground, 419, 429, 595

TABLE, atomic weights and equivalents, 45
— comparative conductivity of commercial copper, 18
— conductors, 577
— E.P.S. cells, 477
— incandescent lamps, 550
— sines and tangents, 98
— specific resistances, 17
— temperature co-efficients, 19
Tangent galvanometer, 98
— — field of force in, 99
— — laws governing, 100
— — Post-Office form, 102
— scale, 102
Tangents and sines, table of, 98
Teeth, Pacinotti, 348, 362
Temperature and heat, 179, 527
— of the arc, 495
Terminals, 30
Terrestrial magnetism, components of, 94
Test, the loop, 154
Testing condition of cells, 169
— efficiency of motors, 433
— vacua, 545
Thomson, Elihu, welding by transformers, 459
— Sir W., graded ammeter, 118
— -Houston blower, 397
— — dynamo, 391
— — regulator, 395
Three-way switch, 606
— -wire system, 583, 595
Tin, melting-point of, 610
Torque, 405
Torricellian vacuum, 535
Tramway, Electric, Blackpool, 413
— — Northfleet, 428
— — Smith, Holroyd, 418
Transformer, Faraday, 448
— Ferranti, 452
— Gramme ring as a, 451
— Mordey, 454
— simple, 450
— Statter, 457
— Thomson, for welding, 459
— Varley, 452
Transformers, 444, 580
— distribution by, 461
— leakage in, 464
— rate of alternation in, 455

TRA ZIN

Transformers, regulation of, 461
— requirements of, 449
— safety devices for, 464
— self-induction in, 463
— series and parallel, 461
Transmission of energy, 402, 444, 576
Treatment of new secondary cells, 483, 486
Two electric states, 1
— -part commutator, 271

UNDERGROUND mains, 419, 429, 595
Unit B.A., 15
— Board of Trade, 615
— magnet-pole, 93
— of heat, 180
— — light, 557
Units, fundamental and derived, 40
— practical, 12
Universal photometer, 574
Upward cell, 69

VACUA, deterioration of, in incandescent lamps, 544
— high, 544
Vacuum testing, 545
— Torricellian, 535
Varley transformer, 452
Victoria dynamo, 364
— Mordey, alternator, 264
Volatilisation of carbons, 497
Volt, the, 12
Voltameter, 467
Voltmeter, Ayrton and Perry's low-reading, 190, 461
— Cardew, 179
— — low-reading, 189
— Evershed, 197
— Thomson, electrostatic, 198
Voltmeters, electro-magnetic, 195
— joining up, 195

WALL socket, 608
Waste of power in conductors, 444, 577
Watt, the, 39
Weak currents, galvanometer for, 170
Welding, transformer for, 459
Werdemann lamp, 503
Wheatstone alternator, 244
— bridge. *See* Bridge
Winding electro-magnets, various methods of, 220
Woodhouse and Rawson switches, 605
Work, unit of, 41
Wrought- and cast-iron for field-magnets 294

ZINC, consumption of, in cells, 79
— -carbon cell, 47
— slabs for dynamo bedplates, 338

PRINTED BY
SPOTTISWOODE AND CO., NEW-STREET SQUARE
LONDON

GENERAL LISTS OF WORKS

PUBLISHED BY

MESSRS. LONGMANS, GREEN, & CO.

LONDON AND NEW YORK.

* * *

HISTORY, POLITICS, HISTORICAL MEMOIRS, &c.

Abbey and Overton's English Church in the Eighteenth Century. Cr. 8vo. 7*s.* 6*d.*

Arnold's Lectures on Modern History. 8vo. 7*s.* 6*d.*

Bagwell's Ireland under the Tudors. Vols. 1 and 2. 8vo. 32*s.* Vol. 3. [*In the press.*

Ball's Legislative Systems in Ireland, 1172–1800. 8vo. 6*s.*

— The Reformed Church of Ireland, 1537–1886. 8vo. 7*s.* 6*d.*

Boultbee's History of the Church of England. Pre-Reformation Period. 8vo. 15*s.*

Bowen's (Sir G. F.) Thirty Years of Colonial Government: a Selection of Official Papers. 2 vols. 8vo. 32*s.*

Buckle's History of Civilisation. 3 vols. crown 8vo. 24*s.*

Churchill's (Lord Randolph) Speeches. 2 vols. 8vo. 24*s.*

Cox's (Sir G. W.) General History of Greece. Crown 8vo. Maps, 7*s.* 6*d.*

Creighton's Papacy during the Reformation. 8vo. Vols. 1 & 2, 32*s.* Vols. 3 & 4, 24*s.*

Curzon's Russia in Central Asia in 1889. With Maps. Illustrated. 8vo. 21*s.*

De Redcliffe's (Viscount Stratford) Life. By Stanley Lane-Poole. 2 vols. 8vo. 36*s.*

De Tocqueville's Democracy in America. 2 vols. crown 8vo. 16*s.*

Doyle's English in America: Virginia, Maryland, and the Carolinas, 8vo. 18*s.*

— — — The Puritan Colonies, 2 vols. 8vo. 36*s.*

Freeman's Historical Geography of Europe. 2 vols. 8vo. 31*s.* 6*d.*

Froude's English in Ireland in the 18th Century. 3 vols. crown 8vo. 18*s.*

— History of England. Popular Edition. 12 vols. crown 8vo. 3*s.* 6*d.* each.

— Short Studies on Great Subjects. 4 vols. crown 8vo. 24*s.*

Gardiner's History of England from the Accession of James I. to the Outbreak of the Civil War. 10 vols. crown 8vo. 60*s.*

— History of the Great Civil War. 1642–1649 (3 vols.) Vol. 1, 1642–1644, 8vo. 21*s.* Vol. 2, 1644–1647, 8vo. 24*s.*

Gibbs' England in South Africa. 8vo. 5*s.*

Godolphin's (Earl of) Life. By the Hon. Hugh Elliot. 8vo. 15*s.*

Greville's Journal of the Reigns of King George IV., King William IV., and Queen Victoria. Cabinet Edition. 8 vols. crown 8vo. 6*s.* each.

Historic Towns. Edited by E. A. Freeman, D.C.L. and the Rev. William Hunt, M.A. With Maps and Plans. Crown 8vo. 3*s.* 6*d.* each.

London. By W. E. Loftie.
Exeter. By E. A. Freeman.
Cinque Ports. By Montagu Burrows.
Bristol. By the Rev. W. Hunt.
Oxford. By the Rev. C. W. Boase.
Colchester. By the Rev. E. C. Cutts.
Carlisle. By the Rev. M. Creighton.
Winchester. By G. W. Kitchin, D.D.

Hurlbert's France and her Republic: a Record of 1839. 8vo.

Lecky's History of England in the Eighteenth Century. Vols. 1 & 2, 1700–1760, 8vo. 36s. Vols. 3 & 4, 1760–1784, 8vo. 36s. Vols. 5 & 6, 1784–1793, 36s.
— History of European Morals. 2 vols. crown 8vo. 16s.
— — — Rationalism in Europe. 2 vols. crown 8vo. 16s.
Longman's Life and Times of Edward III. 2 vols. 8vo. 28s.
Macaulay's Complete Works. Library Edition. 8 vols. 8vo. £5. 5s.
— — — Cabinet Edition. 16 vols. crown 8vo. £4. 16s.
— History of England :—
Popular Edition. 2 vols. cr. 8vo. 5s.
Student's Edition. 2 vols. cr. 8vo. 12s.
People's Edition. 4 vols. cr. 8vo. 16s.
Cabinet Edition. 8 vols. post 8vo. 48s.
Library Edition. 5 vols. 8vo. £4.

Macaulay's Critical and Historical Essays, with Lays of Ancient Rome In One Volume :—
Authorised Edition. Cr. 8vo. 2s. 6d. or 3s. 6d. gilt edges.
Popular Edition. Cr. 8vo. 2

Macaulay's Critical and Historical Essays :—
Student's Edition. 1 vol. cr. 8vo. 6s.
Trevelyan Edition. 2 vols. cr. 8vo 9s.
People's Edition. 2 vols. cr. 8vo. 8s.
Cabinet Edition. 4 vols. post 8vo. 24s.
Library Edition. 3 vols. 8vo. 36s.

Macaulay's Miscellaneous Writings. 2 vols. 8vo. 21s. 1 vol. crown 8vo. 4s. 6d.
— Miscellaneous Writings and Speeches :—
Popular Edition. Cr. 8vo. 2s. 6d.
Student's Edition. Cr. 8vo. 6s.
— Miscellaneous Writings, Speeches, Lays of Ancient Rome, &c. Cabinet Edition. 4 vols. crown 8vo. 24s.
— Writings, Selections from. Crown 8vo. 6s.
— Speeches corrected by Himself. Crown 8vo. 3s. 6d.
Magnus's Outlines of Jewish History. Fcp. 8vo. 3s. 6d.
Malmesbury's (Earl of) Memoirs of an Ex-Minister. Crown 8vo. 7s. 6d.
May's Constitutional History of England, 1760–1870. 3 vols. crown 8vo. 18s.
Melbourne Papers (The). Edited by Lloyd C. Sanders. 8vo. 18s.
Merivale's Fall of the Roman Republic. 12mo. 7s. 6d.
— General History of Rome, B.C. 753–A.D. 476. Crown 8vo. 7s. 6d.
— History of the Romans under the Empire. 8 vols. post 8vo. 48s.
Murdock's Reconstruction of Europe, from the Rise to the Fall of the Second French Empire. Crown 8vo. 9s.
Nelson's (Lord) Letters and Despatches. Edited by J. K. Laughton. 8vo. 16s.
Pears' The Fall of Constantinople. 8vo. 16s.
Porter's History of the Corps of Royal Engineers. 2 vols. 8vo. 36s.
Rawlinson's The History of Phœnicia. 8vo. 24s.
Russell's (Lord John) Life. By Spencer Walpole. 2 vols. 8vo. 36s.
Seebohm's Oxford Reformers—Colet, Erasmus, & More. 8vo. 14s.
Short's History of the Church of England. Crown 8vo. 7s. 6d.
Smith's Carthage and the Carthaginians. Crown 8vo. 6s.
Stubbs' History of the University of Dublin. 8vo. 12s. 6d.
Taylor's Manual of the History of India. Crown 8vo. 7s. 6d.
Tuttle's History of Prussia under Frederick the Great, 1740–1756. 2 vols. cr. 8vo. 18s.
Walpole's History of England, from 1815. 5 vols. 8vo. Vols. 1 & 2, 1815–1832, 36s. Vol. 3, 1832–1841, 18s. Vols. 4 & 5, 1841–1858, 36s.
Wylie's History of England under Henry IV. Vol. 1, crown 8vo. 10s. 6d.

EPOCHS OF ANCIENT HISTORY.

Edited by the Rev. Sir G. W. Cox, Bart. M.A. and by C. Sankey, M.A.
10 volumes, fcp. 8vo. with Maps, price 2*s*. 6*d*. each.

- **The Gracchi, Marius, and Sulla. By A. H. Beesly, M.A. With 2 Maps.**
- **The Early Roman Empire. By the Rev. W. Wolfe Capes, M.A. With 2 Maps.**
- **The Roman Empire of the Second Century. By the Rev. W. Wolfe Capes, M.A. With 2 Maps.**
- **The Athenian Empire from the Flight of Xerxes to the Fall of Athens. By the Rev. Sir G. W. Cox, Bart. M.A. With 5 Maps.**
- **The Rise of the Macedonian Empire. By Arthur M. Curteis, M.A. With 8 Maps.**
- **The Greeks and the Persians. By the Rev. Sir G. W. Cox, Bart. With 4 Maps.**
- **Rome to its Capture by the Gauls. By Wilhelm Ihne. With a Map.**
- **The Roman Triumvirates. By the Very Rev. Charles Merivale, D.D. With Map.**
- **The Spartan and Theban Supremacies. By Charles Sankey, M.A. With 5 Maps.**
- **Rome and Carthage, the Punic Wars. By R. Bosworth Smith. With 9 Maps.**

EPOCHS OF MODERN HISTORY.

Edited by C. Colbeck, M.A. 19 volumes, fcp. 8vo. with Maps. Price 2*s*. 6*d*. each.

- **The Beginning of the Middle Ages. By the Very Rev. R. W. Church. With 3 Maps.**
- **The Normans in Europe. By Rev. A. H. Johnson, M.A. With 3 Maps.**
- **The Crusades. By the Rev. Sir G. W. Cox, Bart. M.A. With a Map.**
- **The Early Plantagenets. By the Right Rev. W. Stubbs, D.D. With 2 Maps.**
- **Edward the Third. By the Rev. W. Warburton, M.A. With 3 Maps.**
- **The Houses of Lancaster and York. By James Gairdner. With 5 Maps.**
- **The Early Tudors. By the Rev. C. E. Moberly, M.A.**
- **The Era of the Protestant Revolution. By F. Seebohm. With 4 Maps.**
- **The Age of Elizabeth. By the Rev. M. Creighton, M.A. LL.D. With 5 Maps.**
- **The First Two Stuarts. By Samuel Rawson Gardiner. With 4 Maps.**
- **The Thirty Years' War, 1618–1648. By Samuel Rawson Gardiner. With a Map.**
- **The English Restoration and Louis XIV., 1648–1678. By Osmund Airy.**
- **The Fall of the Stuarts. By the Rev. Edward Hale, M.A. With 11 Maps.**
- **The Age of Anne. By E. E. Morris, M.A. With 7 Maps and Plans.**
- **The Early Hanoverians. By E. E. Morris, M.A. With 9 Maps and Plans.**
- **Frederick the Great and the Seven Years' War. By F. W. Longman. With 2 Maps.**
- **The War of American Independence, 1775–1783. By J. M. Ludlow. With 4 Maps.**
- **The French Revolution, 1789–1795. By Mrs. S. R. Gardiner. With 7 Maps.**
- **The Epoch of Reform, 1830–1850. By Justin McCarthy, M.P.**

EPOCHS OF CHURCH HISTORY.

Edited by the Rev. Mandell Creighton. Fcp. 8vo. price 2*s*. 6*d*. each.

- **The English Church in other Lands. By the Rev. H. W. Tucker.**
- **The History of the Reformation in England. By the Rev. George G. Perry.**
- **The Church of the Early Fathers. By Alfred Plummer, D.D.**
- **The Evangelical Revival in the Eighteenth Century. By the Rev. J. H. Overton.**
- **A History of the University of Oxford. By the Hon. G. C. Brodrick, D.C.L.**
- **A History of the University of Cambridge. By J. Bass Mullinger, M.A.**
- **The English Church in the Middle Ages. By Rev. W. Hunt, M.A.**
- **The Arian Controversy. By H. M. Gwatkin, M.A.**
- **Wycliffe and Movements for Reform. By Reginald L. Poole.**
- **The Counter-Reformation. By A. W. Ward.**
- **The Church and the Roman Empire. By the Rev. A. Carr.**
- **The Church and the Puritans, 1570–1660. By Henry Offley Wakeman.**
- **The Church and the Eastern Empire. By the Rev. H. F. Tozer.**
- **Hildebrand and His Times. By the Rev. W. R. W. Stephens.**
- **The Popes and the Hohenstaufen. By Ugo Balzani.**

BIOGRAPHICAL WORKS.

Armstrong's (E. J.) Life and Letters. Edited by G. F. Armstrong. Fcp. 8vo. 7*s*. 6*d*.

Bacon's Life and Letters, by Spedding. 7 vols. 8vo. £4. 4*s*.

Bagehot's Biographical Studies. 1 vol. 8vo. 12*s*.

Burdett's Prince, Princess, and People: the Public Life and Works of T.R.H. the Prince and Princess of Wales. 8vo. 21*s*.

Carlyle's (Mrs.) Letters and Memorials. 3 vols. 8vo. 36*s*.

Clavers, the Despot's Champion. By A Southern. Crown 8vo. 7*s*. 6*d*.

English Worthies. Edited by Andrew Lang. Crown 8vo. each 1*s*. sewed; 1*s*. 6*d*. cloth.

Charles Darwin. By Grant Allen.
Shaftesbury (The First Earl). By H. D. Traill.
Admiral Blake. By David Hannay.
Marlborough. By Geo. Saintsbury.
Steele. By Austin Dobson.
Ben Jonson. By J. A. Symonds.
George Canning. By Frank H. Hill.
Claverhouse. By Mowbray Morris.

Fox (Charles James) The Early History of. By Sir G. O. Trevelyan. Cr. 8vo. 6*s*.

Froude's Cæsar: a Sketch. Crown 8vo. 3*s*. 6*d*.

Hamilton's (Sir W. R.) Life, by Graves. 3 vols. 8vo. 15*s*. each.

Havelock's Life, by Marshman. Crown 8vo. 3*s*. 6*d*.

Jenkin's (Fleeming) Papers, Literary, Scientific, &c. With Memoir by R. L. Stevenson. 2 vols. 8vo. 32*s*.

Laughton's Studies in Naval History. 8vo. 10*s*. 6*d*.

Macaulay's (Lord) Life and Letters. By his Nephew, Sir G. O. Trevelyan, Bart. Popular Edition, 1 vol. cr. 8vo. 2*s*. 6*d*. Student's Edition, 1 vol. cr. 8vo. 6*s*. Cabinet Edition, 2 vols. post 8vo. 12*s*. Library Edition, 2 vols. 8vo. 36*s*.

McDougall's Memoirs (Bishop of Labuan). By C. J. Bunyon. 8vo. 14*s*.

Mendelssohn's Letters. Translated by Lady Wallace. 2 vols. cr. 8vo. 5*s*. each.

Müller's (Max) Biographical Essays. Crown 8vo. 7*s*. 6*d*.

Newman's Apologia pro Vitâ Suâ. Crown 8vo. 6*s*.

Pasteur (Louis) His Life and Labours. Crown 8vo. 7*s*. 6*d*.

Shakespeare, Outline of the Life of. By J. O. Halliwell-Phillipps. Illustrated. 2 vols. royal 8vo. 21*s*.

Shakespeare's True Life. By James Walter. With 500 Illustrations. Imp. 8vo. 21*s*.

Southey's Correspondence with Caroline Bowles. 8vo. 14*s*.

Stephen's Essays in Ecclesiastical Biography. Crown 8vo. 7*s*. 6*d*.

Vignoles' (C. B.) Life. By his Son. 8vo. 16*s*.

Wellington's Life, by Gleig. Crown 8vo. 6*s*.

MENTAL AND POLITICAL PHILOSOPHY, FINANCE, &c.

Adams' Public Debts; an Essay on the Science of Finance. 8vo. 12*s*. 6*d*.

Amos' View of the Science of Jurisprudence. 8vo. 18*s*.

— **Primer of the English Constitution.** Crown 8vo. 6*s*.

Bacon's Essays, with Annotations by Whately. 8vo. 10*s*. 6*d*.

— Works, edited by Spedding. 7 vols. 8vo. 73*s*. 6*d*.

Bagehot's Economic Studies, edited by Hutton. 8vo. 10*s*. 6*d*.

Bain's Logic, Deductive and Inductive. Crown 8vo. 10*s*. 6*d*.

Part I. Deduction, 4*s*. | Part II. Induction, 6*s*. 6*d*.

— Mental and Moral Science. Crown 8vo. 10*s*. 6*d*.

— The Senses and the Intellect. 8vo. 15*s*.

— The Emotions and the Will. 8vo. 15*s*.

Barnett's Practicable Socialism. Crown 8vo. 2*s*. 6*d*.

Blake's Tables for the Conversion of 5 per cent. Interest from $\frac{1}{16}$ to 7 per cent. 8vo, 12*s*. 6*d*.

Case's Physical Realism. 8vo. 15s.

Crump's Short Enquiry into the Formation of English Political Opinion. 8vo. 7s. 6d.

— Causes of the Great Fall in Prices. 8vo. 6s.

Dowell's A History of Taxation and Taxes in England. 8vo. Vols. 1 & 2, 21s. Vols. 3 & 4, 21s.

Green's (Thomas Hill) Works. (3 vols.) Vols. 1 & 2, Philosophical Works. 8vo. 16s. each. Vol. 3, Miscellanies. With Memoir. 8vo. 21s.

Hume's Essays, edited by Green & Grose. 2 vols. 8vo. 28s.

— Treatise of Human Nature, edited by Green & Grose. 2 vols. 8vo. 28s.

Kirkup's An Enquiry into Socialism. Crown 8vo. 5s.

Ladd's Elements of Physiological Psychology. 8vo. 21s.

Lang's Custom and Myth: Studies of Early Usage and Belief. Crown 8vo. 7s. 6d.

— Myth, Ritual, and Religion. 2 vols. crown 8vo. 21s.

Leslie's Essays in Political Economy. 8vo. 10s. 6d.

Lewes's History of Philosophy. 2 vols. 8vo. 32s.

Lubbock's Origin of Civilisation. Illustrated. 8vo. 18s.

Macleod's The Elements of Economics. 2 vols. crown 8vo. 7s. 6d. each.

— The Elements of Banking. Crown 8vo. 5s.

— The Theory and Practice of Banking. Vol. 1, 8vo. 12s. Vol. 2, 14s.

— The Theory of Credit. (2 vols. 8vo.) Vol. 1, 7s. 6d. Vol. 2 *[In the press.*

Max Müller's The Science of Thought. 8vo. 21s.

Mill's (James) Analysis of the Phenomena of the Human Mind. 2 vols. 8vo. 28s.

Mill (John Stuart) on Representative Government. Crown 8vo. 2s.

— — on Liberty. Crown 8vo. 1s. 4d.

— — Examination of Hamilton's Philosophy. 8vo. 16s.

— — Logic. Crown 8vo. 5s.

— — Principles of Political Economy. 2 vols. 8vo. 30s. People's Edition, 1 vol. crown 8vo. 5s.

— — Utilitarianism. 8vo. 5s.

— — Three Essays on Religion, &c. 8vo. 5s.

Mulhall's History of Prices since 1850. Crown 8vo. 6s.

Sandars' Institutes of Justinian, with English Notes. 8vo. 18s.

Seebohm's English Village Community. 8vo. 16s.

Sully's Outlines of Psychology. 8vo. 12s. 6d.

— Teacher's Handbook of Psychology. Crown 8vo. 6s. 6d.

Swinburne's Picture Logic. Post 8vo. 5s.

Thompson's A System of Psychology. 2 vols. 8vo. 36s.

— The Problem of Evil. 8vo. 10s. 6d.

— The Religious Sentiments of the Human Mind. 8vo. 7s. 6d.

— Social Progress: an Essay. 8vo. 7s. 6d.

Webb's The Veil of Isis. 8vo. 10s. 6d.

Whately's Elements of Logic. Crown 8vo. 4s. 6d.

— — — Rhetoric. Crown 8vo. 4s. 6d.

Zeller's History of Eclecticism in Greek Philosophy. Crown 8vo. 10s. 6d.

— Plato and the Older Academy. Crown 8vo. 18s.

— Pre-Socratic Schools. 2 vols. crown 8vo. 30s.

— Socrates and the Socratic Schools. Crown 8vo. 10s. 6d.

— Stoics, Epicureans, and Sceptics. Crown 8vo. 15s.

— Outlines of the History of Greek Philosophy. Crown 8vo. 10s. 6d.

CLASSICAL LANGUAGES AND LITERATURE.

Æschylus, The Eumenides of. Text, with Metrical English Translation, by J. F. Davies. 8vo. 7*s*.

Aristophanes' The Acharnians, translated by R. Y. Tyrrell. Crown 8vo. 2*s*. 6*d*.

Aristotle's The Ethics, Text and Notes, by Sir Alex. Grant, Bart. 2 vols. 8vo. 32*s*.

— The Nicomachean Ethics, translated by Williams, crown 8vo. 7*s*. 6*d*.

— The Politics, Books I. III. IV. (VII.) with Translation, &c. by Bolland and Lang. Crown 8vo. 7*s*. 6*d*.

Becker's *Charicles* and *Gallus*, by Metcalfe. Post 8vo. 7*s*. 6*d*. each.

Cicero's Correspondence, Text and Notes, by R. Y. Tyrrell. Vols. 1 & 2, 8vo. 12*s*. each.

Plato's Parmenides, with Notes, &c. by J. Maguire. 8vo. 7*s*. 6*d*.

Virgil's Works, Latin Text, with Commentary, by Kennedy. Crown 8vo. 10*s*. 6*d*.

— Æneid, translated into English Verse, by Conington. Crown 8vo. 6*s*.

— — — — — — by W. J. Thornhill. Cr. 8vo. 7*s*. 6*d*.

— Poems, — — — Prose, by Conington. Crown 8vo. 6*s*.

Witt's Myths of Hellas, translated by F. M. Younghusband. Crown 8vo. 3*s*. 6*d*.

— The Trojan War, — — Fcp. 8vo. 2*s*.

— The Wanderings of Ulysses, — Crown 8vo. 3*s*. 6*d*.

ENCYCLOPÆDIAS, DICTIONARIES, AND BOOKS OF REFERENCE.

Acton's Modern Cookery for Private Families. Fcp. 8vo. 4*s*. 6*d*.

Ayre's Treasury of Bible Knowledge. Fcp. 8vo. 6*s*.

Blake's Tables for the Conversion of 5 per Cent. Interest, &c. 8vo. 12*s*. 6*d*.

Chisholm's Handbook of Commercial Geography. 29 Maps. 8vo. 16*s*.

Gwilt's Encyclopædia of Architecture. 8vo. 52*s*. 6*d*.

Keith Johnston's Dictionary of Geography, or General Gazetteer. 8vo. 42*s*.

Longmans' New Atlas. 56 Maps. Edited by G. G. Chisholm. 4to. or imperial 8vo. 12*s*. 6*d*.

M'Culloch's Dictionary of Commerce and Commercial Navigation. 8vo. 63*s*.

Maunder's Biographical Treasury. Fcp. 8vo. 6*s*.

— Historical Treasury. Fcp. 8vo. 6*s*.

— Scientific and Literary Treasury. Fcp. 8vo. 6*s*.

— Treasury of Bible Knowledge, edited by Ayre. Fcp. 8vo. 6*s*.

— Treasury of Botany, edited by Lindley & Moore. Two Parts, 12*s*.

— Treasury of Geography. Fcp. 8vo. 6*s*.

— Treasury of Knowledge and Library of Reference. Fcp. 8vo. 6*s*.

— Treasury of Natural History. Fcp. 8vo. 6*s*.

Quain's Dictionary of Medicine. Medium 8vo. 31*s*. 6*d*., or in 2 vols. 34*s*.

Reeve's Cookery and Housekeeping. Crown 8vo. 5*s*.

Rich's Dictionary of Roman and Greek Antiquities. Crown 8vo. 7*s*. 6*d*.

Roget's Thesaurus of English Words and Phrases. Crown 8vo. 10*s*. 6*d*.

Willich's Popular Tables, by Marriott. Crown 8vo. 10*s*. 6*d*.

CHEMISTRY, ENGINEERING, & GENERAL SCIENCE.

Abbott's Elementary Theory of the Tides. Crown 8vo. *2s.*
Allen's (Grant) Force and Energy: a Theory of Dynamics. 8vo. *7s. 6d.*
Arnott's Elements of Physics or Natural Philosophy. Crown 8vo. *12s. 6d.*
Bourne's Catechism of the Steam Engine. Crown 8vo. *7s. 6d.*
— **Handbook of the Steam Engine.** Fcp. 8vo. *9s.*
— **Recent Improvements in the Steam Engine.** Fcp. 8vo. *6s.*
Clerk's The Gas Engine. With Illustrations. Crown 8vo. *7s. 6d.*
Clodd's The Story of Creation. Illustrated. Crown 8vo. *6s.*
Crookes's Select Methods in Chemical Analysis. 8vo. *24s.*
Culley's Handbook of Practical Telegraphy. 8vo. *16s.*
Earl's Elements of Laboratory Work. Crown 8vo. *4s. 6d.*
Fairbairn's Useful Information for Engineers. 3 vols. crown 8vo. *31s. 6d.*
— **Mills and Millwork.** 1 vol. 8vo. *25s.*
Forbes' Lectures on Electricity. Crown 8vo. *5s.*
Galloway's Principles of Chemistry Practically Taught. Crown 8vo. *6s. 6d.*
Ganot's Elementary Treatise on Physics, by Atkinson. Large crown 8vo. *15s.*
— **Natural Philosophy, by Atkinson.** Crown 8vo. *7s. 6d.*
Gibson's Text-Book of Elementary Biology. Crown 8vo. *6s.*
Harrison's The Creation and Physical Structure of the Earth. 8vo. *7s. 6d.*
Haughton's Six Lectures on Physical Geography. 8vo. *15s.*
Helmholtz on the Sensations of Tone. Royal 8vo. *28s.*
Helmholtz's Lectures on Scientific Subjects. 2 vols. crown 8vo. *7s. 6d.* each.
Herschel's Outlines of Astronomy. Square crown 8vo. *12s.*
Hjelt's General Organic Chemistry. Crown 8vo. [*In the press.*
Hudson and Gosse's The Rotifera or 'Wheel Animalcules.' With 34 Plates. 6 parts. 4to. *10s. 6d.* each. Supplement, *12s. 6d.* Complete, 2 vols. 4to. with Supplement, *£4. 4s.*
Hullah's Lectures on the History of Modern Music. 8vo. *8s. 6d.*
— **Transition Period of Musical History.** 8vo. *10s. 6d.*
Jago's Inorganic Chemistry, Theoretical and Practical. Fcp. 8vo. *2s. 6d.*
Jeans' Handbook for the Stars. Royal 8vo. *5s.*
Kolbe's Short Text-Book of Inorganic Chemistry. Crown 8vo. *7s. 6d.*
Lloyd's Treatise on Magnetism. 8vo. *10s. 6d.*
Macalister's Zoology and Morphology of Vertebrate Animals. 8vo. *10s. 6d.*
Macfarren's Lectures on Harmony. 8vo. *12s.*
— **Addresses and Lectures.** Crown 8vo. *6s. 6d.*
Martin's Navigation and Nautical Astronomy. Royal 8vo. *18s.*
Meyer's Modern Theories of Chemistry. 8vo. *18s.*
Miller's Elements of Chemistry, Theoretical and Practical. 3 vols. 8vo. Part I. Chemical Physics, *16s.* Part II. Inorganic Chemistry, *24s.* Part III. Organic Chemistry, price *31s. 6d.*
Mitchell's Manual of Practical Assaying. 8vo. *31s. 6d.*
— **Dissolution and Evolution and the Science of Medicine.** 8vo. *16s.*
Noble's Hours with a Three-inch Telescope. Crown 8vo. *4s. 6d.*
Northcott's Lathes and Turning. 8vo. *18s.*
Oliver's Astronomy for Amateurs. Crown 8vo. *7s. 6d.*
Owen's Comparative Anatomy and Physiology of the Vertebrate Animals. 3 vols. 8vo. *73s. 6d.*

Richardson's The Commonhealth; a Series of Essays. Crown 8vo. 6*s.*

Schellen's Spectrum Analysis. 8vo. 31*s.* 6*d.*

Scott's Weather Charts and Storm Warnings. Crown 8vo. 6*s.*

Sennett's Treatise on the Marine Steam Engine. 8vo. 21*s.*

Slingo & Brooker's Electrical Engineering for Electric Light Artisans. Crown 8vo. 10*s.* 6*d.*

Smith's Graphics, or the Art of Calculation by Drawing Lines. Part I. with Atlas of Plates, 8vo. 15*s.*

Stoney's The Theory of the Stresses on Girders, &c. Royal 8vo. 36*s.*

Thorpe's Dictionary of Applied Chemistry. 3 vols. Vol. 1, 42*s.*

Tilden's Practical Chemistry. Fcp. 8vo. 1*s.* 6*d.*

Tyndall's Faraday as a Discoverer. Crown 8vo. 3*s.* 6*d.*

— Floating Matter of the Air. Crown 8vo. 7*s.* 6*d.*

— Fragments of Science. 2 vols. post 8vo. 16*s.*

— Heat a Mode of Motion. Crown 8vo. 12*s.*

— Lectures on Light delivered in America. Crown 8vo. 5*s.*

— Lessons on Electricity. Crown 8vo. 2*s.* 6*d.*

— Notes on Electrical Phenomena. Crown 8vo. 1*s.* sewed, 1*s.* 6*d.* cloth.

— Notes of Lectures on Light. Crown 8vo. 1*s.* sewed, 1*s.* 6*d.* cloth.

— Researches on Diamagnetism and Magne-Crystallic Action. Cr. 8vo. 12*s.*

— Sound, with Frontispiece and 203 Woodcuts. Crown 8vo. 10*s.* 6*d.*

Unwin's The Testing of Materials of Construction. Illustrated. 8vo. 21*s.*

Watts' Dictionary of Chemistry. New Edition (4 vols.). Vols. 1 and 2, 8vo. 42*s.* each.

Webb's Celestial Objects for Common Telescopes. Crown 8vo. 9*s.*

NATURAL HISTORY, BOTANY, & GARDENING.

Bennett and Murray's Handbook of Cryptogamic Botany. 8vo. 16*s.*

Dixon's Rural Bird Life. Crown 8vo. Illustrations, 5*s.*

Hartwig's Aerial World, 8vo. 10*s.* 6*d.*

— Polar World, 8vo. 10*s.* 6*d.*

— Sea and its Living Wonders. 8vo. 10*s.* 6*d.*

— Subterranean World, 8vo. 10*s.* 6*d.*

— Tropical World, 8vo. 10*s.* 6*d.*

Lindley's Treasury of Botany. 2 vols. fcp. 8vo. 12*s.*

Loudon's Encyclopædia of Gardening. 8vo. 21*s.*

— — Plants. 8vo. 42*s.*

Rivers's Orchard House. Crown 8vo. 5*s.*

— Miniature Fruit Garden. Fcp. 8vo. 4*s.*

Stanley's Familiar History of British Birds. Crown 8vo. 3*s.* 6*d.*

Wood's Bible Animals. With 112 Vignettes. 8vo. 10*s.* 6*d.*

— Homes Without Hands, 8vo. 10*s.* 6*d.*

— Insects Abroad, 8vo. 10*s.* 6*d.*

— Insects at Home. With 700 Illustrations. 8vo. 10*s.* 6*d.*

— Out of Doors. Crown 8vo. 5*s.*

— Petland Revisited. Crown 8vo. 3*s.* 6*d.*

— Strange Dwellings. Crown 8vo. 3*s.* 6*d.*

THEOLOGICAL AND RELIGIOUS WORKS.

Arnold's (Rev. Dr. Thomas) Sermons. 6 vols. crown 8vo. 5*s.* each.

Boultbee's Commentary on the 39 Articles. Crown 8vo. 6*s.*

Browne's (Bishop) Exposition of the 39 Articles. 8vo. 16*s.*

Bullinger's Critical Lexicon and Concordance to the English and Greek New Testament. Royal 8vo. 15*s.*

Colenso on the Pentateuch and Book of Joshua. Crown 8vo. 6*s.*

Conder's Handbook of the Bible. Post 8vo. 7*s.* 6*d.*

Conybeare & Howson's Life and Letters of St. Paul :—

  Library Edition, with Maps, Plates, and Woodcuts. 2 vols. square crown 8vo. 21*s.*

  Student's Edition, revised and condensed, with 46 Illustrations and Maps. 1 vol. crown 8vo. 6*s.*

Davidson's Introduction to the Study of the New Testament. 2 vols. 8vo. 30*s.*

Edersheim's Life and Times of Jesus the Messiah. Library Edition. **2 vols. 8vo. 24*s.*** Cabinet Edition. (Abridged.) Crown 8vo. 7*s.* 6*d.*

  — **Prophecy and History in relation to the Messiah. 8vo. 12*s.***

Ellicott's (Bishop) Commentary on St. Paul's Epistles. 8vo. Corinthians I. 16*s.* Galatians, 8*s.* 6*d.* Ephesians, 8*s.* 6*d.* **Pastoral Epistles, 10*s.* 6*d.*** Philippians, **Colossians and Philemon, 10*s.* 6*d.* Thessalonians, 7*s.* 6*d.***

  — — **Lectures on the Life of our Lord. 8vo. 12*s.***

Ewald's Antiquities of Israel, translated by Solly. 8vo. 12*s.* 6*d.*

  — **History of Israel, translated by Carpenter & Smith. 8 vols. 8vo. Vols. 1 & 2, 24*s.* Vols. 3 & 4, 21*s.* Vol. 5, 18*s.* Vol. 6, 16*s.* Vol. 7, 21*s.* Vol. 8, 18*s.***

Hobart's Medical Language of St. Luke. 8vo. 16*s.*

Hopkins's Christ the Consoler. Fcp. 8vo. 2*s.* 6*d.*

Hutchinson's The Record of a Human Soul. Fcp. 8vo. 3*s.* 6*d.*

Jameson's Sacred and Legendary Art. 6 vols. square 8vo.

  Legends of the Madonna. 1 vol. 21*s.*

  — — — **Monastic Orders. 1 vol. 21*s.***

  — — — **Saints and Martyrs. 2 vols. 31*s.* 6*d.***

  — — — **Saviour. Completed by Lady Eastlake. 2 vols. 42*s.***

Jukes's New Man and the Eternal Life. Crown 8vo. 6*s.*

  — **Second Death and the Restitution of all Things. Crown 8vo. 3*s.* 6*d.***

  — **Types of Genesis. Crown 8vo. 7*s.* 6*d.***

  — **The Mystery of the Kingdom. Crown 8vo. 3*s.* 6*d.***

  — **The Names of God in Holy Scripture. Crown 8vo. 4*s.* 6*d.***

Lyra Germanica : Hymns translated by Miss Winkworth. Fcp. 8vo. 5*s.*

Macdonald's (G.) Unspoken Sermons. First and Second Series. Crown 8vo. 3*s.* 6*d.* each. Third Series. Crown 8vo. 7*s.* 6*d.*

  — **The Miracles of our Lord. Crown 8vo. 3*s.* 6*d.***

Manning's Temporal Mission of the Holy Ghost. Crown 8vo. 8*s.* 6*d.*

Martineau's Endeavours after the Christian Life. Crown 8vo. 7*s.* 6*d.*

  — **Hymns of Praise and Prayer. Crown 8vo. 4*s.* 6*d.* 32mo. 1*s.* 6*d.***

  — **Sermons, Hours of Thought on Sacred Things. 2 vols. 7*s.* 6*d.* each.**

Max Müller's Origin and Growth of Religion. Crown 8vo. 7*s.* 6*d.*

  — — **Science of Religion. Crown 8vo. 7*s.* 6*d.***

  — — **Gifford Lectures on Natural Religion. Crown 8vo. 10*s.* 6*d.***

Mozley's The Word. Crown 8vo. 7*s.* 6*d.*

Newman's Apologia pro Vitâ Suâ. Crown 8vo. 6s.
— The Arians of the Fourth Century. Crown 8vo. 6s.
— The Idea of a University Defined and Illustrated. Crown 8vo. 7s.
— Historical Sketches. 3 vols. crown 8vo. 6s. each.
— Discussions and Arguments on Various Subjects. Crown 8vo. 6s.
— An Essay on the Development of Christian Doctrine. Crown 8vo. 6s.
— Certain Difficulties Felt by Anglicans in Catholic Teaching Considered. Vol. 1, crown 8vo. 7s. 6d. Vol. 2, crown 8vo. 5s. 6d.
— The Via Media of the Anglican Church, Illustrated in Lectures, &c. 2 vols. crown 8vo. 6s. each.
— Essays, Critical and Historical. 2 vols. crown 8vo. 12s.
— Essays on Biblical and on Ecclesiastical Miracles. Crown 8vo. 6s.
— Present Position of Catholics in England. Crown 8vo. 7s. 6d.
— An Essay in Aid of a Grammar of Assent. 7s. 6d.
— Select Treatises of St. Athanasius in Controversy with the Arians. Translated. 2 vols. crown 8vo. 15s.

Newnham's The All-Father. Sermons. With Preface by Edna Lyall. Cr. 8vo. 4s. 6d.

Perring's The 'Work and Days' of Moses. 3s. 6d.

Reply to Dr. Lightfoot's Essays. By the Author of 'Supernatural Religion.' 8vo. 6s.

Roberts' Greek the Language of Christ and His Apostles. 8vo. 18s.

Supernatural Religion. Complete Edition. 3 vols. 8vo. 36s.

Twells' Colloquies on Preaching. Crown 8vo. 5s.

Younghusband's The Story of Our Lord told in Simple Language for Children. Illustrated. Crown 8vo. 2s. 6d. cloth.
— The Story of Genesis. Crown 8vo. 2s. 6d. cloth.

TRAVELS, ADVENTURES, &c.

Baker's Eight Years in Ceylon. Crown 8vo. 5s.
— Rifle and Hound in Ceylon. Crown 8vo. 5s.

Brassey's Sunshine and Storm in the East. Library Edition, 8vo. 21s. Cabinet Edition, crown 8vo. 7s. 6d. Popular Edition, 4to. 6d.
— Voyage in the 'Sunbeam.' Library Edition, 8vo. 21s. Cabinet Edition, cr. 8vo. 7s. 6d. School Edit. fcp. 8vo. 2s. Popular Edit. 4to. 6d.
— In the Trades, the Tropics, and the 'Roaring Forties.' Cabinet Edition, crown 8vo. 17s. 6d. Popular Edition, 4to. 6d.
— Last Journals, 1886-7. Illustrated. 8vo. 21s.

Bryden's Kloof and Karroo. Sport, Legend, &c., in Cape Colony. 8vo. 10s. 6d.

Cecil's Notes of my Journey Round the World. 8vo. 12s. 6d.

Clutterbuck's The Skipper in Arctic Seas. Illustrated. Crown 8vo. 10s. 6d.

Coolidge's Swiss Travel and Swiss Guide-Books. Crown 8vo. 10s. 6d.

Crawford's Reminiscences of Foreign Travel. Crown 8vo. 5s.

Deland's Florida Days. Illustrated. 4to. 21s.

Froude's Oceana; or, England and her Colonies. Cr. 8vo. 2s. boards; 2s. 6d. cloth.
— The English in the West Indies. Crown 8vo. 2s. boards; 2s. 6d. cloth.

Howitt's Visits to Remarkable Places. Crown 8vo. 5s.

James's The Long White Mountain; or, a Journey in Manchuria. 8vo. 24s.

Lees and Clutterbuck's B.C. 1887: a Ramble in British Columbia. Cr. 8vo. 6s.

Lindt's Picturesque New Guinea. 4to. 42s.

Norton's Guide Book to Florida.

Pennell's Our Sentimental Journey through France and Italy. Cr. 8vo. 6s.

Riley's Athos; or, The Mountain of the Monks. 8vo. 21s.

Smith's The White Umbrella in Mexico. Fcp. 8vo. 6s. 6d.

Three in Norway. By Two of Them. Crown 8vo. 2s. boards; 2s. 6d. cloth.

Willoughby's East Africa and its Big Game. 8vo. 21s.

WORKS BY RICHARD A PROCTOR.

Old and New Astronomy. 12 Parts, 2*s.* 6*d.* each. Supplementary Section, 1*s.* Complete in 1 vol. 4to. 36*s.* [*In course of publication.*
The Orbs Around Us. With Chart and Diagrams. Crown 8vo. 5*s.*
Other Worlds than Ours. With 14 Illustrations. Crown 8vo. 5*s.*
The Moon. With Plates, Charts, Woodcuts, and Photographs. Crown 8vo. 5*s.*
Universe of Stars. With 22 Charts and 22 Diagrams. 8vo. 10*s.* 6*d.*
Light Science for Leisure Hours. 3 vols. crown 8vo. 5*s.* each.
Chance and Luck. Crown 8vo. 2*s.* boards; 2*s.* 6*d.* cloth.
Larger Star Atlas for the Library, in 12 Circular Maps. Folio, 15*s.*
New Star Atlas, in 12 Circular Maps (with 2 Index Plates). Crown 8vo. 5*s.*
The Student's Atlas. 12 Circular Maps. 8vo. 5*s.*
Transits of Venus. With 20 Lithographic Plates and 38 Illustrations. 8vo. 8*s.* 6*d.*
Studies of Venus-Transits. With 7 Diagrams and 10 Plates. 8vo. 5*s.*
Elementary Physical Geography. With 33 Maps and Woodcuts. Fcp. 8vo. 1*s.* 6*d.*
Lessons in Elementary Astronomy. With 47 Woodcuts. Fcp. 8vo. 1*s.* 6*d.*
First Steps in Geometry. Fcp. 8vo. 3*s.* 6*d.*
Easy Lessons in the Differential Calculus. Fcp. 8vo. 2*s.* 6*d.*
How to Play Whist, with the Laws and Etiquette of Whist. Crown 8vo. 3*s.* 6*d.*
Home Whist: an Easy Guide to Correct Play. 16mo. 1*s.*
The Poetry of Astronomy. Crown 8vo. 5*s.*
The Stars in their Seasons. Imperial 8vo. 5*s.*
Strength. With 9 Illustrations. Crown 8vo. 2*s.*
Strength and [illegible]iness. With 9 Illustrations. Crown 8vo. 5*s.*
The Seasons Pictured in Forty-eight Sun-Views of the Earth, and Twenty-four Zodiacal Maps and other Drawings. Demy 4to. 6*s.*
The Star Primer; showing the Starry Sky, week by week. Crown 4to. 2*s.* 6*d.*
Nature Studies. By Grant Allen, A. Wilson, E. Clodd, and R. A. Proctor. Cr. 8vo. 5*s.*
Leisure Readings. By E. Clodd, A. Wilson, and R. A. Proctor, &c. Cr. 8vo. 5*s.*
Rough Ways Made Smooth. Crown 8vo. 5*s.*
Our Place Among Infinities. Crown 8vo. 5*s.*
The Expanse of Heaven: Essays on the Wonders of the Firmament. Crown 8vo. 5*s.*
Pleasant Ways in Science. Crown 8vo. 5*s.*
Myths and Marvels of Astronomy. Crown 8vo. 5*s.*
The Great Pyramid: Observatory, Tomb, and Temple. Crown 8vo. 5*s.*

AGRICULTURE, HORSES, DOGS, AND CATTLE.

Fitzwygram's Horses and Stables. 8vo. 5*s.*
Lloyd's The Science of Agriculture. 8vo. 12*s.*
Loudon's Encyclopædia of Agriculture. 21*s.*
Prothero's Pioneers and Progress of English Farming. Crown 8vo. 5*s.*
Steel's Diseases of the Ox, a Manual of Bovine Pathology. 8vo. 15*s.*
— — — Dog. 8vo. 10*s.* 6*d.*
Stonehenge's Dog in Health and Disease. Square crown 8vo. 7*s.* 6*d.*
Taylor's Agricultural Note Book. Fcp. 8vo. 2*s.* 6*d.*
Ville on Artificial Manures, by Crookes. 8vo. 21*s.*
Youatt's Work on the Dog. 8vo. 6*s.*
— — — — Horse. 8vo. 7*s.* 6*d.*

WORKS OF FICTION.

By H. RIDER HAGGARD.
She: a History of Adventure. Illustrated. 3s. 6d.
Allan Quatermain. Illustrated. 3s. 6d.
Maiwa's Revenge. 2s. bds.; 2s. 6d. cl.
Colonel Quaritch. 3s. 6d.
Cleopatra. Illustrated. 6s.
Beatrice. 6s.

By the EARL OF BEACONSFIELD.
Vivian Grey.
Venetia.
Coningsby.
Lothair.
Tancred.
Sybil.
Alroy, Ixion, &c.
Endymion.
The Young Duke.
Contarini Fleming.
Henrietta Temple.
Price 1s. each, bds.; 1s. 6d. each, cloth.
The HUGHENDEN EDITION. With 2 Portraits and 11 Vignettes. 11 vols. Crown 8vo. 42s.

By G. J. WHYTE-MELVILLE.
The Gladiators.
The Interpreter.
Holmby House.
Good for Nothing.
Kate Coventry.
Digby Grand.
General Bounce.
Queen's Maries.
Price 1s. each, bds.; 1s. 6d. each, cloth.

By ELIZABETH M. SEWELL.
Amy Herbert.
Gertrude.
Ursula.
Cleve Hall.
Ivors.
Earl's Daughter.
The Experience of Life.
A Glimpse of the World.
Katharine Ashton.
Margaret Percival.
Laneton Parsonage.
1s. 6d. each, cloth; 2s. 6d. each, gilt edges.

By Mrs. MOLESWORTH.
Marrying and Giving in Marriage. Price 2s. 6d.

By DOROTHEA GERARD.
Orthodox. Price 6s.

By MAY KENDALL.
Such is Life. 6s.

By Mrs. OLIPHANT.
In Trust.
Madam.
Price 1s. each, bds.: 1s. 6d. each, cloth.
Lady Car. 2s. 6d.

By G. H. JESSOP.
Judge Lynch. 6s.
Gerald Ffrench's Friends. 6s.

By A. C. DOYLE.
Micah Clarke. 3s. 6d.
The Captain of the Polestar, &c.

By G. G. A. MURRAY.
Gobi or Shamo. 6s.

By JAMES PAYN.
The Luck of the Darrells.
Thicker than Water.
1s. each, boards; 1s. 6d. each, cloth.

By ANTHONY TROLLOPE.
The Warden.
Barchester Towers.
1s. each, boards; 1s. 6d. each, cloth.

By BRET HARTE.
In the Carquinez Woods. Price 1s. boards; 1s. 6d. cloth.
On the Frontier.
By Shore and Sedge.
Price 1s. each, sewed.

By ROBERT L. STEVENSON.
The Dynamiter.
Strange Case of Dr. Jekyll and Mr. Hyde.
1s. each, sewed; 1s. 6d. each, cloth.

By R. L. STEVENSON and L. OSBOURNE.
The Wrong Box. 5s.

By EDNA LYALL.
The Autobiography of a Slander. Price 1s. sewed.

By F. ANSTEY.
The Black Poodle, and other Stories. Price 2s. boards; 2s. 6d. cloth.

By the AUTHOR OF THE 'ATELIER DU LYS.'
The Atelier du Lys. 2s. 6d.
Mademoiselle Mori. 2s. 6d.
In the Olden Time. 2s. 6d.
Hester's Venture. 2s. 6d.

By Mrs. DELAND.
John Ward, Preacher. 2s. boards; 2s. 6d. cloth.

By W. HERRIES POLLOCK.
A Nine Men's Morrice. 6s.

By CHRISTIE MURRAY & HY. HERMAN.
Wild Darrie. 6s.

By CHRISTIE MURRAY & HY. MURRAY.
A Dangerous Catspaw. 2s. 6d.

By J. A. FROUDE.
The Two Chiefs of Dunboy. 6s.

By JAMES BAKER.
By the Western Sea. 6s.

By W. E. NORRIS.
Mrs. Fenton: a Sketch. 6s.

POETRY AND THE DRAMA.

Armstrong's (Ed. J.) Poetical Works. Fcp. 8vo. 5s.
— (G. F.) Poetical Works:—
Poems, Lyrical and Dramatic. Fcp. 8vo. 6s.
Ugone: a Tragedy. Fcp. 8vo. 6s.
A Garland from Greece. Fcp. 8vo. 9s.
King Saul. Fcp. 8vo. 5s.
King David. Fcp. 8vo. 6s.
King Solomon. Fcp. 8vo. 6s.
Stories of Wicklow. Fcp. 8vo. 9s.
Mephistopheles in Broadcloth: a Satire. Fcp. 8vo. 4s.
Victoria Regina et Imperatrix: a Jubilee Song from Ireland, 1887. 4to. 2s. 6d.

Ballads of Books. Edited by Andrew Lang. Fcp. 8vo. 6s.
Bowen's Harrow Songs and other Verses. Fcp. 8vo. 2s. 6d.
Bowdler's Family Shakespeare. Medium 8vo. 14s. 6 vols. fcp. 8vo. 21s.
Deland's The Old Garden, and other Verses. Fcp. 8vo. 5s.
Fletcher's Character Studies in Macbeth. Crown o. 2s. 6d.
Goethe's Faust, translated by Birds Crown 8vo. Part 6s.; Part II. 6s.
— — translated by Webb. 8vo. 12s. 6d.
— — edited by Selss. Crown 8vo. 5s.
Higginson's The Afternoon Landscape. Fcp. 8vo. 5s.
Ingelow's Poems. 2 Vols. fcp. 8vo. 12s.; Vol. 3, fcp. 8vo. 5s.
— Lyrical and other Poems. Fcp. 8vo. 2s. 6d. cloth, plain; 3s. cloth, gilt edges.
Kendall's (May) Dreams to Sell. Fcp. 8vo. 6s.
Lang's Grass of Parnassus. Fcp. 8vo. 6s.
Macaulay's Lays of Ancient Rome. Illustrated by Scharf. 4to. 10s. 6d. Bijou Edition, fcp. 8vo. 2s. 6d. Popular Edit., fcp. 4to. 6d. swd., 1s. cloth.
— Lays of Ancient Rome with Ivry and the Armada. Illustrated by Weguelin. Crown 8vo. 3s. 6d. gilt edges.
Nesbit's Lays and Legends. Crown 8vo. 5s.
— Leaves of Life. Crown 8vo. 5s.
Newman's The Dream of Gerontius. 16mo. 6d. sewed; 1s. cloth.
— Verses on Various Occasions. Fcp. 8vo. 6s.
Reader's Voices from Flowerland: a Birthday Book. 2s. 6d. cloth, 3s. 6d. roan.
— Echoes of Thought: a Medley of Verse. Crown 8vo. 5s.
Riley's Old-Fashioned Roses. Fcp. 8vo. 5s.
Smith's (Gregory) Fra Angelico, and other short Poems. Crown 8vo. 4s. 6d.
Southey's Poetical Works. Medium 8vo. 14s.
Stevenson's A Child's Garden of Verses. Fcp. 8vo. 5s.
Sumner's The Besom Maker, and other Country Folk Songs. 4to. 2s. 6d.
Tomson's The Bird Bride. Fcp. 8vo. 6s.
Virgil's Æneid, translated by Conington. Crown 8vo. 6s.
— Poems, translated into English Prose. Crown 8vo. 6s.

SPORTS AND PASTIMES.

Campbell-Walker's Correct Card, or How to Play at Whist. Fcp. 8vo. 2s. 6d.
Ford's Theory and Practice of Archery, revised by W. Butt. 8vo. 14s.
Francis's Treatise on Fishing in all its Branches. Post 8vo. 15s.
Longman's Chess Openings. Fcp. 8vo. 2s. 6d.
Pole's Theory of the Modern Scientific Game of Whist. Fcp. 8vo. 2s. 6d.
Proctor's How to Play Whist. Crown 8vo. 3s. 6d.
— Home Whist. 18mo. 1s. sewed.
Ronalds's Fly-Fisher's Entomology. 8vo. 14s.
Wilcocks's Sea-Fisherman. Post 8vo. 6s.

MISCELLANEOUS WORKS.

A. K. H. B., The Essays and Contributions of. Crown 8vo. 3*s*. 6*d*.

Autumn Holidays of a Country Parson
Changed Aspects of Unchanged Truths.
Common-Place Philosopher in Town and Country.
Critical Essays of a Country Parson.
Counsel and Comfort spoken from a City Pulpit.
East Coast Days and Memories.
Graver Thoughts of a Country Parson. Three Series.
Landscapes, Churches, and Moralities.
Leisure Hours in Town.
Lessons of Middle Age.
Our Homely Comedy; and Tragedy.
Our Little Life. Essays Consolatory and Domestic. Two Series.
Present-day Thoughts.
Recreations of a Country Parson. Three Series.
Seaside Musings on Sundays and Week-Days.
Sunday Afternoons in the Parish Church of a University City.

'To Meet the Day' through the Christian Year. 4*s*. 6*d*.

Archer's Masks or Faces? A Study in the Psychology of Acting. Cr 8vo. 6*s*. 6*d*.
Armstrong's (Ed. J.) Essays and Sketches. Fcp. 8vo. 5*s*.
Arnold's (Dr. Thomas) Miscellaneous Works. 8vo 7*s*. 6*d*.
Bagehot's Literary Studies, edited by Hutton. 2 vols. 8vo. 28*s*.
Baker's War with Crime. Reprinted Papers. 8vo. 12*s*. 6*d*.
Blue Fairy Book (The). Edited by Andrew Lang. Illustrated. Crown 8vo. 6*s*.
Book (The) of Wedding Days. Illustrated by Walter Crane. 4to. 21*s*.
Farrar's Language and Languages. Crown 8vo. 6*s*.
Henderson's The Story of Music. Crown 8vo. 6*s*.
Huth's The Marriage of Near Kin. Royal 8vo. 21*s*.
Jefferies' Field and Hedgerow: Last Essays. Crown 8vo. 6*s*.
Lang's Books and Bookmen. Crown 8vo. 6*s*. 6*d*.
— Letters on Literature. Fcp. 8vo. 6*s*. 6*d*.
— Old Friends: Essays in Epistolary Parody. [*In the press.*
Lavigerie (Cardinal) and the African Slave-Trade. 8vo. 14*s*.
Matthews' (Brander) Pen and Ink. Reprinted Papers. Crown 8vo. 5*s*.
Max Müller's Lectures on the Science of Language. 2 vols. crown 8vo. 16*s*.
— — **Lectures on India. 8vo. 12*s*. 6*d*.**
— — **Biographies of Words and the Home of the Aryas. Crown 8vo. 7*s*. 6*d*.**
Rendle and Norman's Inns of Old Southwark. Illustrated. Royal 8vo. 28*s*.
Wendt's Papers on Maritime Legislation. Royal 8vo. £1. 11*s*. 6*d*.

WORKS BY MR. SAMUEL BUTLER.

Op. 1. Erewhon. 5*s*.
Op. 2. The Fair Haven. 7*s*. 6*d*.
Op. 3. Life and Habit. 7*s*. 6*d*.
Op. 4. Evolution, Old and New. 10*s*. 6*d*.
Op. 5. Unconscious Memory. 7*s*. 6*d*.
Op. 6. Alps and Sanctuaries of Piedmont and the Canton Ticino. 10*s*. 6*d*.
Op. 7. Selections from Ops. 1–6. 7*s*. 6*d*.
Op. 8. Luck, or Cunning. 7*s*. 6*d*.
Op. 9. Ex Voto. 10*s*. 6*d*.
Holbein's 'La Danse.' 3*s*.

WORKS BY MRS. DE SALIS.

Cakes and Confections. 1*s*. 6*d*.
Entrées à la Mode Fcp. 8vo. 1*s*. 6*d*.
Game and Poultry à la Mode. 1*s*. 6*d*.
Oysters à la Mode. Fcp. 8vo. 1*s*. 6*d*.
Puddings and Pastry à la Mode. 1*s*. 6*d*.
Savouries à la Mode. Fcp. 8vo. 1*s*.
Soups and Dressed Fish à la Mode. Fcp. 8vo. 1*s*. 6*d*.
Sweets & Supper Dishes à la Mode. 1*s*. 6*d*.
Vegetables à la Mode. Fcp. 8vo. 1*s*. 6*d*.
Wrinkles and Notions for Every Household. Crown 8vo. 2*s*. 6*d*

LONGMANS, GREEN, & CO., London and New York.

MEDICAL AND SURGICAL WORKS.

Ashby's Notes on Physiology for the Use of Students. 134 Illustrations. 18mo. 5s.
Ashby and Wright's The Diseases of Children, Medical and Surgical. 8vo. 21s.
Barker's Short Manual of Surgical Operations. With 61 Woodcuts. Cr. 8vo. 12s. 6d.
Bennett's Clinical Lectures on Varicose Veins. 8vo. 6s.
Bentley's Text-book of Organic Materia Medica. 62 Illustrations. Cr. 8vo. 7s. 6d.
Coats's Manual of Pathology. With 339 Illustrations. 8vo. 31s. 6d.
Cooke's Tablets of Anatomy. Post 4to. 7s. 6d.
Dickinson's Renal and Urinary Affections. Complete in Three Parts, 8vo. with 12 Plates and 122 Woodcuts. £3. 4s. 6d. cloth.
— The Tongue as an Indication of Disease. 8vo. 7s. 6d.
Erichsen's Science and Art of Surgery. 1,025 Engravings. 2 vols. 8vo. 48s.
— Concussion of the Spine, &c. Crown 8vo. 10s. 6d.
Gairdner and Coats's Lectures on Tabes Mesenterica. 28 Illustrations. 8vo. 12s. 6d.
Garrod's (Sir Alfred) Treatise on Gout and Rheumatic Gout. 8vo. 21s.
— — Materia Medica and Therapeutics. Crown 8vo. 12s. 6d.
Garrod's (A. G.) Use of the Laryngoscope. With Illustrations. 8vo. 3s. 6d.
Gray's Anatomy. With 569 Illustrations. Royal 8vo. 36s.
Hassall's San Remo Climatically and Medically Considered. Crown 8vo. 5s.
— The Inhalation Treatment of Disease. Crown 8vo. 12s. 6d.
Hewitt's The Diseases of Women. With 211 Engravings. 8vo. 24s.
Holmes's System of Surgery. 3 vols. royal 8vo. £4. 4s.
Ladd's Elements of Physiological Psychology. With 113 Illustrations. 8vo. 21s.
Little's In-Knee Distortion (Genu Valgum). With 40 Illustrations. 8vo. 7s. 6d.
Liveing's Handbook on Diseases of the Skin. Fcp. 8vo. 5s.
— Notes on the Treatment of Skin Diseases. 18mo. 3s.
— Elephantiasis Græcorum, or True Leprosy. Crown 8vo. 4s. 6d.
Longmore's The Illustrated Optical Manual. With 74 Illustrations. 8vo. 14s.
— Gunshot Injuries. With 58 Illustrations. 8vo. 31s. 6d.
Mitchell's Dissolution and Evolution and the Science of Medicine. 8vo. 16s.
Munk's Euthanasia; or, Medical Treatment in Aid of an Easy Death. Cr. 8vo. 4s. 6d.
Murchison's Continued Fevers of Great Britain. 8vo. 25s.
— Diseases of the Liver, Jaundice, and Abdominal Dropsy. 8vo. 24s.
Owen's Manual of Anatomy for Senior Students. Crown 8vo. 12s. 6d.
Paget's Lectures on Surgical Pathology. With 131 Woodcuts. 8vo. 21s.
— Clinical Lectures and Essays. 8vo. 15s.
Quain's (Jones) Elements of Anatomy. 1,000 Illustrations. 2 vols. 8vo. 18s. each.
Quain's (Dr. Richard) Dictionary of Medicine. With 138 Illustrations. 1 vol. 8vo. 31s. 6d. cloth, or 40s. half-russia. To be had also in 2 vols. 34s. cloth.
Salter's Dental Pathology and Surgery. With 133 Illustrations. 8vo. 18s.
Schäfer's The Essentials of Histology. With 283 Illustrations. 8vo. 6s.
Smith's (H. F.) The Handbook for Midwives. With 41 Woodcuts. Cr. 8vo. 5s.
Smith's (T.) Manual of Operative Surgery on the Dead Body. 46 Illus. 8vo. 12s.
West's Lectures on the Diseases of Infancy and Childhood. 8vo. 18s.
— The Mother's Manual of Children's Diseases. Fcp. 8vo. 2s. 6d.
Wilks and Moxon's Lectures on Pathological Anatomy. 8vo. 18s.
Williams's Pulmonary Consumption. With 4 Plates and 10 Woodcuts. 8vo. 16s.
Wright's Hip Disease in Childhood. With 48 Woodcuts. 8vo. 10s. 6d.